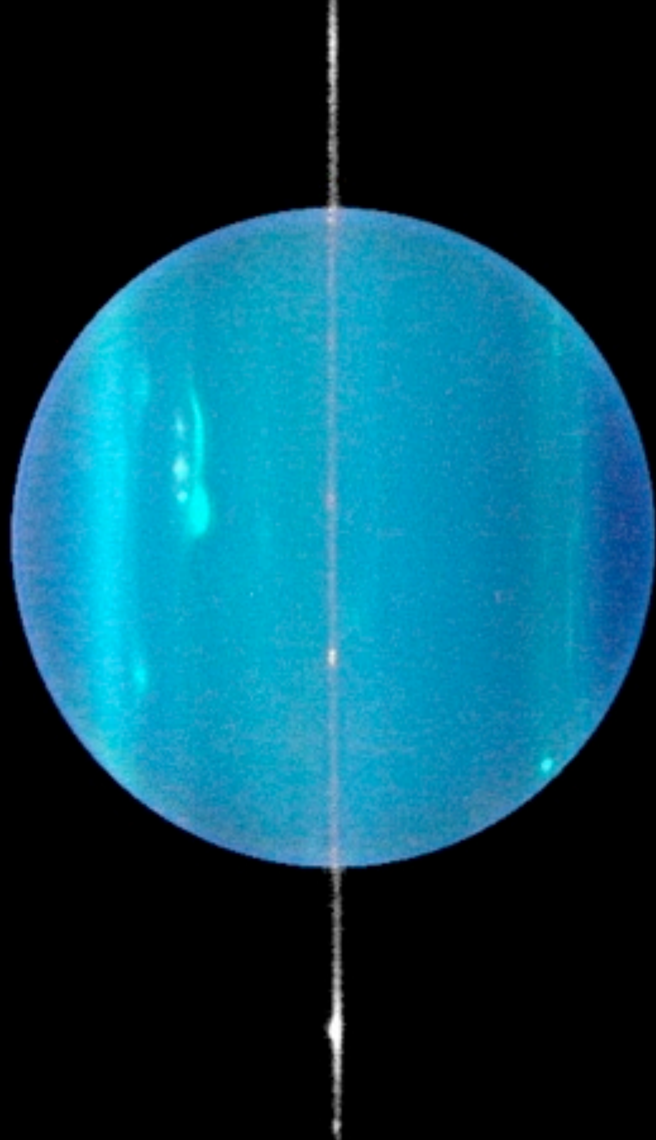
Characterizing Uranus with an Ice Giant Planetary Origins Probe (Ice-POP)



Mark Marley
NASA Ames Research Center
&
Kevin Zahnle,
Nadine Nettelmann &
Jonathan Fortney

Planetary Decadal Survey (2013-2022)

"Third highest priority flagship mission is the Uranus Orbiter and Probe mission"

Today

- Why Uranus and why an atmosphere probe?
- Outline of mission scenario from APL study
- Ongoing Thermal Protection System study at Ames
- Some of the special challenges at Uranus

Why Me?

- Papers on Uranus atmospheric structure and evolution since the ‘90s
- Member of decadal review panel giant planets subcommittee (H. Hammel, chair)
- Science advisor to Ames TPS study

Why a Mission?

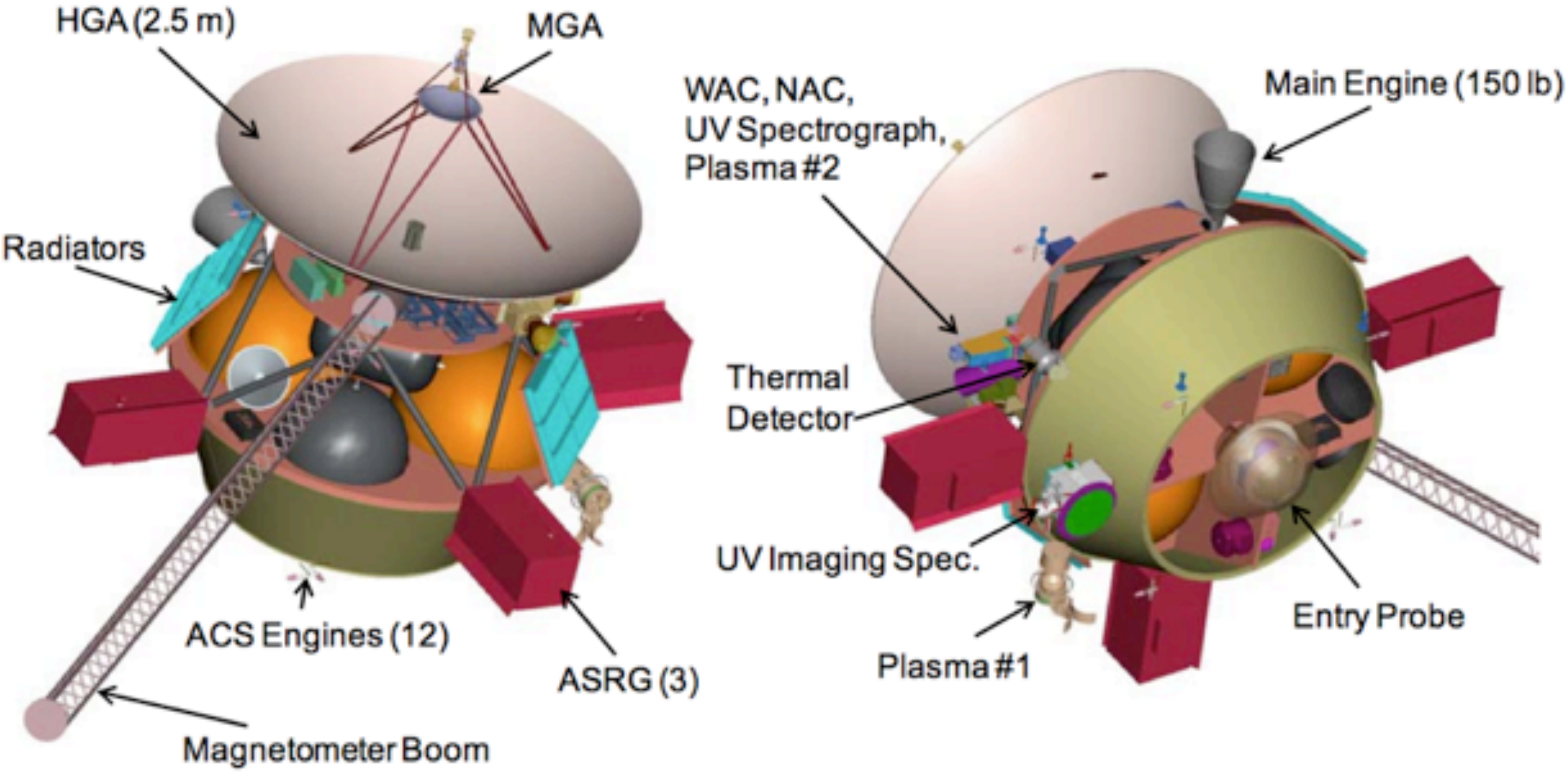


Figure 3-3. Uranus orbiter concept.

Uranus: The Boring Planet

Uranus: The Dynamic ~~Boring~~ Planet

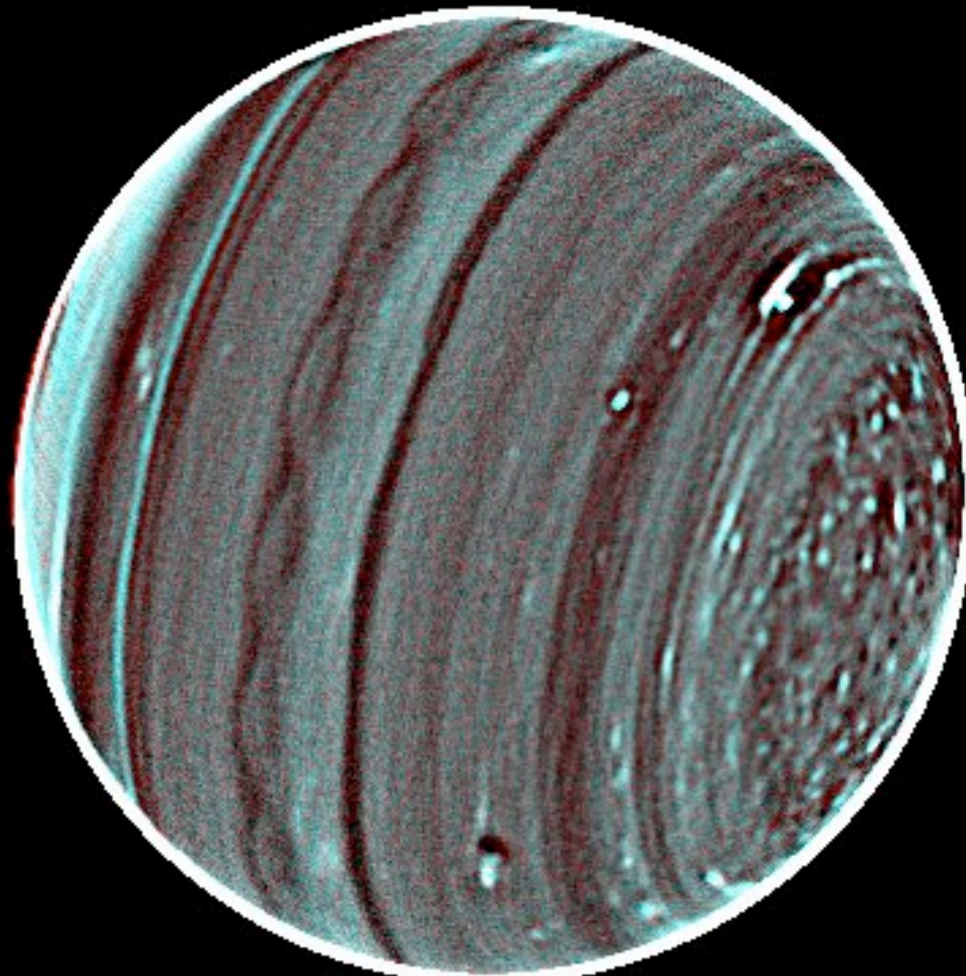
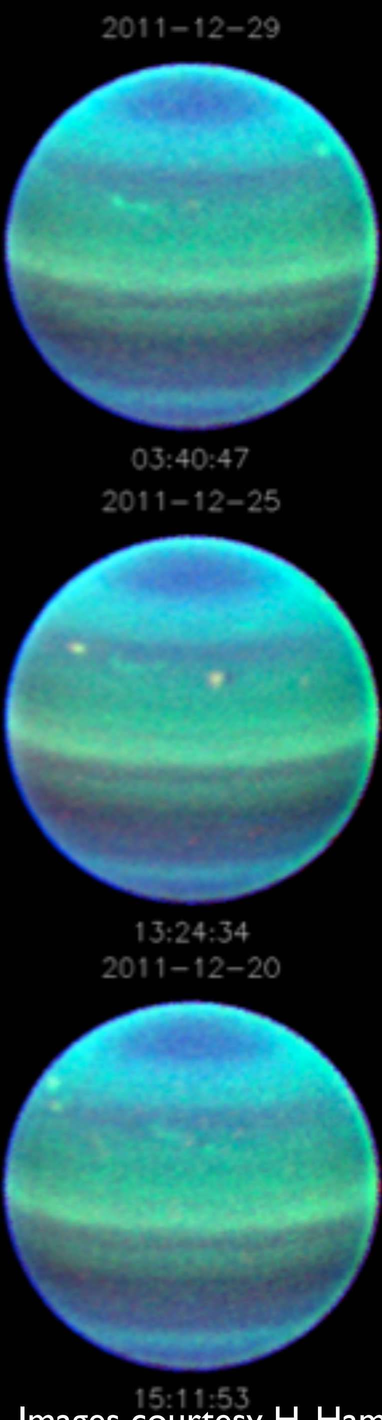


Image courtesy L. Sromovsky, P. Fry, H. Hammel, I. de Pater, Keck Observatory



Images courtesy H. Hammel

- Only visited by *Voyager 2*
- The more accessible ice giant
- Rich science target (magnetic field, atmospheric dynamics, moons...)
- Unsolved problem in solar system formation
- Atmospheric composition contains fingerprint of formation processes
- Ice giants appear to be a common outcome of planet formation---much more common than gas giants

State of Knowledge, Current *

	Jupiter	Saturn	Uranus	Neptune
GP In situ Molecular and elemental abundances	2 (haven't measured H20)	0	0	0
GP Three-dimensional atmospheric composition and temperature	2 (Galileo objectives not completed)	2 (Cassini will make it 3)	1	1
GP Internal structure (dynamo, gravity, deep circulation)	2 (Juno will make it 3)	2 (Cassini will make it 3)	1	1
GP Global energy balance (internal heat flux)	3	2 (Cassini will make it 3)	0 (upper limit only)	1
GP Magnetosphere sources, sinks, processes	2 (Juno will make it 3)	2.5 (Cassini will make it 3)	1	1
GP Upper atmosphere heating & aurorae	2 (Juno will make it 3)	2 (Cassini will make it 3)	1	1
GP Atmospheric dynamics & meteorology	2 (Juno might make it 2.5)	2 (Cassini will make it 2.5)	1	1
Rings structure, composition, dynamics	2	3	2	1
Small satellites - geology and composition	2	2 (Cassini might make it 3)	1	1

0 = no knowledge
1 = very limited knowledge
2 = incomplete knowledge
3 = substantial knowledge

*Factors in Juno & Cassini XXM

State of Knowledge, after Saturn Probe and **Uranus Orbiter/ Probe**

0 = no knowledge
1 = very limited knowledge
2 = incomplete knowledge
3 = substantial knowledge

	Jupiter	Saturn	Uranus	Neptune
GP In situ Molecular and elemental abundances	2 (haven't measured H20)	2 (won't measure H20)	2 (won't measure H20)	0
GP Three-dimensional atmospheric composition and temperature	2 (Galileo objectives not completed)	2 (Cassini will make it 3)	3	1
GP Internal structure (dynamo, gravity, deep circulation)	2 (Juno will make it 3)	2 (Cassini will make it 3)	2	1
GP Global energy balance (internal heat flux)	3	2 (Cassini will make it 3)	3	1
GP Magnetosphere sources, sinks, processes	2 (Juno will make it 3)	2.5 (Cassini will make it 3)	3	1
GP Upper atmosphere heating & aurorae	2 (Juno will make it 3)	2 (Cassini will make it 3)	3	1
GP Atmospheric dynamics & meteorology	2 (Juno might make it 2.5)	2 (Cassini will make it 2.5, SP will make it 3)	3	1
Rings structure, composition, dynamics	2	3	3	1
Small satellites - geology and composition	2	2 (Cassini might make it 3)	3	1

Why a Probe?

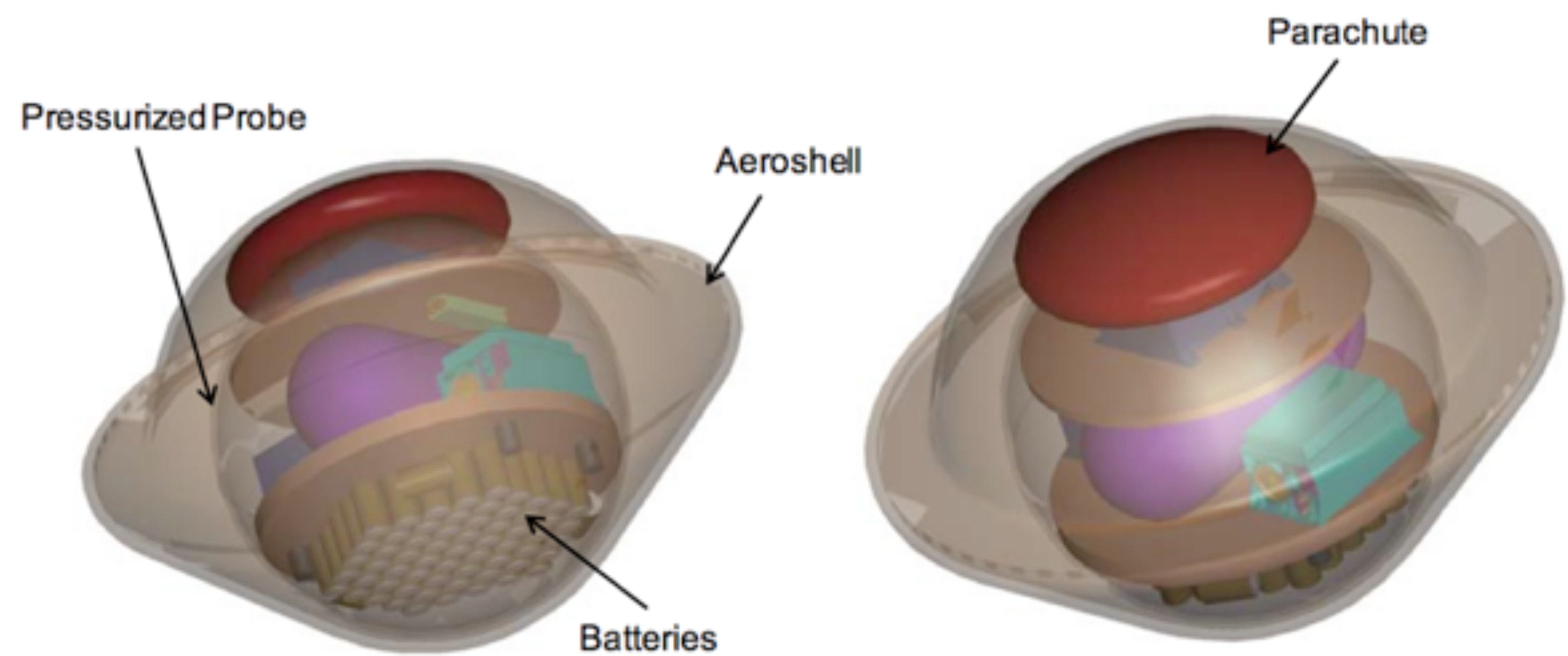
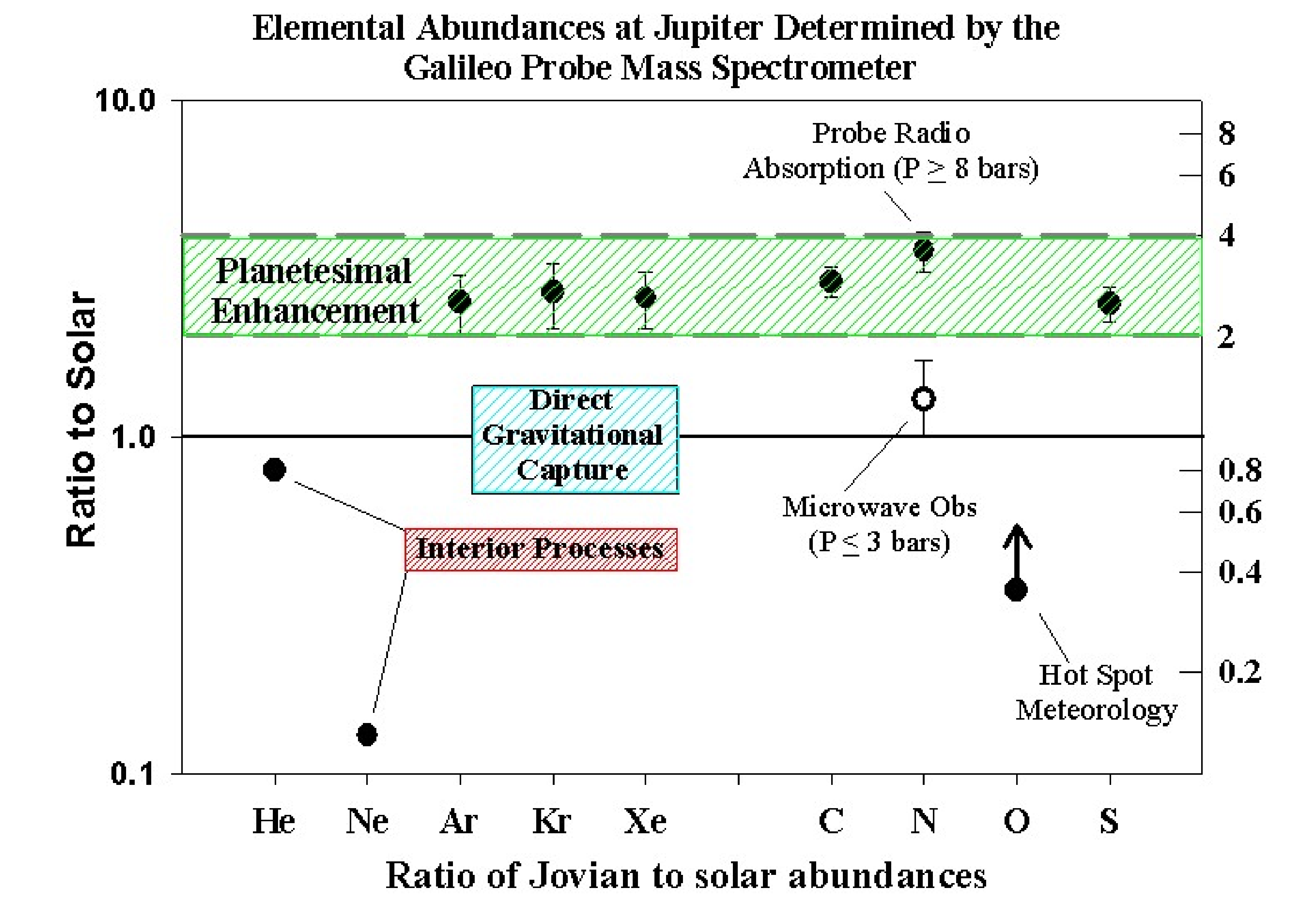
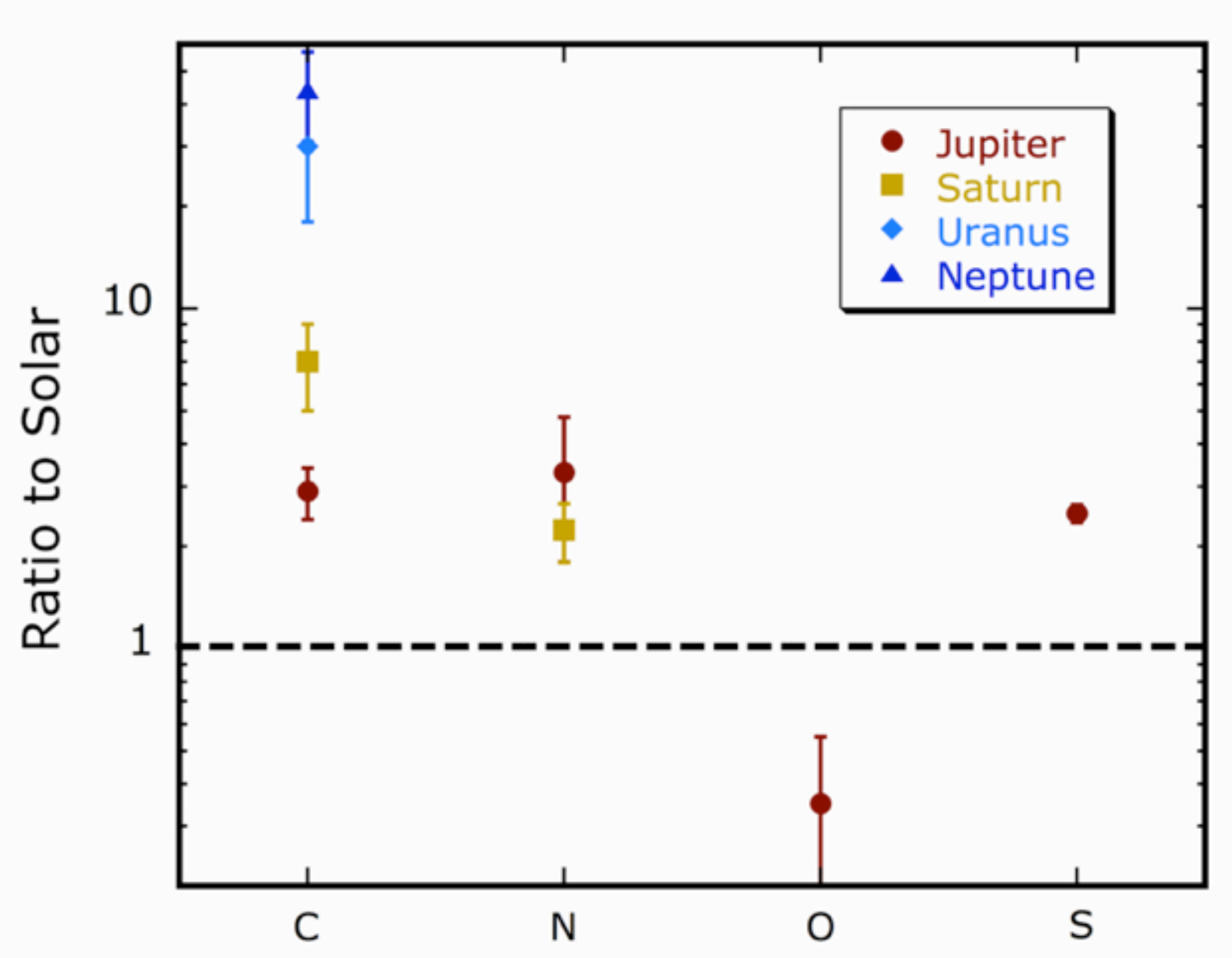


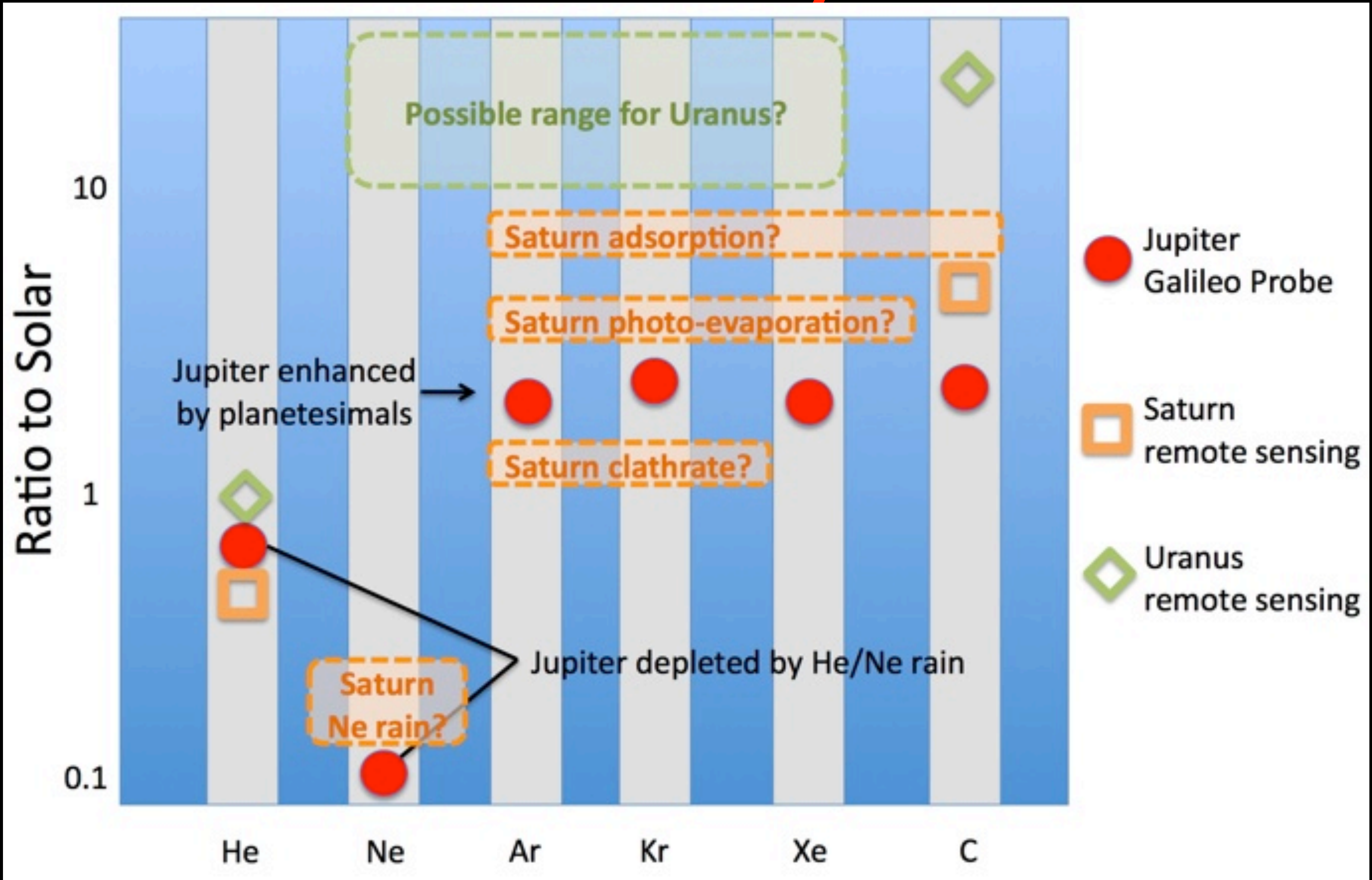
Figure 3-5. Entry probe configuration.



Owen et al. (1999)

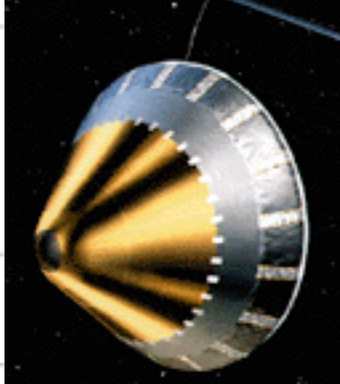

Ratio to Solar
10
1
Jupiter
Saturn
Uranus
Neptune
C
N
O
S

Cosmochemistry of Uranus



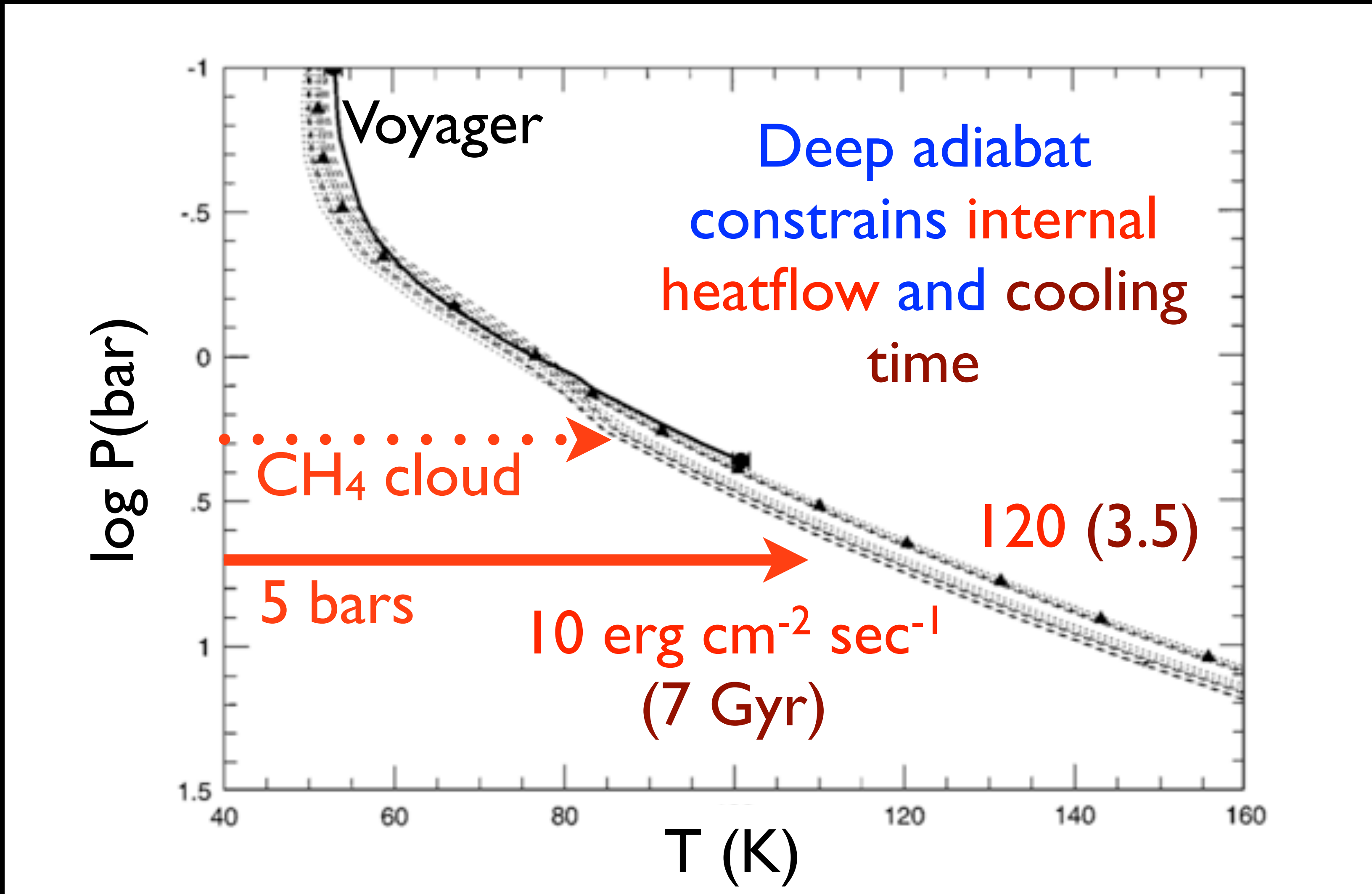
Galileo probe outcomes

1	1996Sci...272..846N	153.000	05/1996	A E R C	Niemann, Hasso B.; Atreya, Sushil K.; Carignan, George R.; Donahue, Thomas M.; Haberman, John A.; Harpold, Dan N.; Hartle, Richard E.; Hunten, Donald M.; Kasprzak, Wayne T.; Mahaffy, Paul R.; and 3 coauthors	The Galileo Probe Mass Spectrometer: Composition of Jupiter's Atmosphere	composition
2	1996Sci...272..844S	66.000	05/1996	A E R C	Seiff, Alvin; Kirk, Donn B.; Knight, Tony C. D.; Mihalov, John D.; Blanchard, Robert C.; Young, Richard E.; Schubert, Gerald; von Zahn, Ulf; Lehmacher, Gerald; Milos, Frank S.; Wang, Jerry	Structure of the Atmosphere of Jupiter: Galileo Probe Measurements	thermal structure
3	1996Sci...272..709A	64.000	05/1996	A E R C	Anderson, J. D.; Sjogren, W. L.; Schubert, G.	Galileo Gravity Results and the Internal Structure of Io	
4	1996Sci...272..839O	47.000	05/1996	A E R C	Orton, G.; Ortiz, J. L.; Baines, K.; Bjoraker, G.; Carsenty, U.; Colas, F.; Dayal, A.; Deming, D.; Drossart, P.; Frappa, E.; and 31 coauthors	Earth-Based Observations of the Galileo Probe Entry Site	
5	1996Sci...272..849V	46.000	05/1996	A E R C	von Zahn, U.; Hunten, D. M.	The Helium Mass Fraction in Jupiter's Atmosphere	He abundance
6	1996Sci...272..842A	41.000	05/1996	A E R C	Atkinson, David H.; Pollack, James B.; Seiff, Alvin	Galileo Doppler Measurements of the Deep Zonal Winds at Jupiter	winds
7	1996Natur.381..395G	37.000	05/1996	A E R C	Grün, E.; Baguhl, M.; Hamilton, D. P.; Riemann, R.; Zook, H. A.; Dermott, S.; Fechtig, H.; Gustafson, B. A.; Hanner, M. S.; Horányi, M.; and 12 coauthors	Constraints from Galileo observations on the origin of jovian dust streams	
8	1996Sci...272..854R	35.000	05/1996	A E R C	Ragent, Boris; Colburn, David S.; Avrin, Philip; Rages, Kathy A.	Results of the Galileo Probe Nephelometer Experiment	clouds



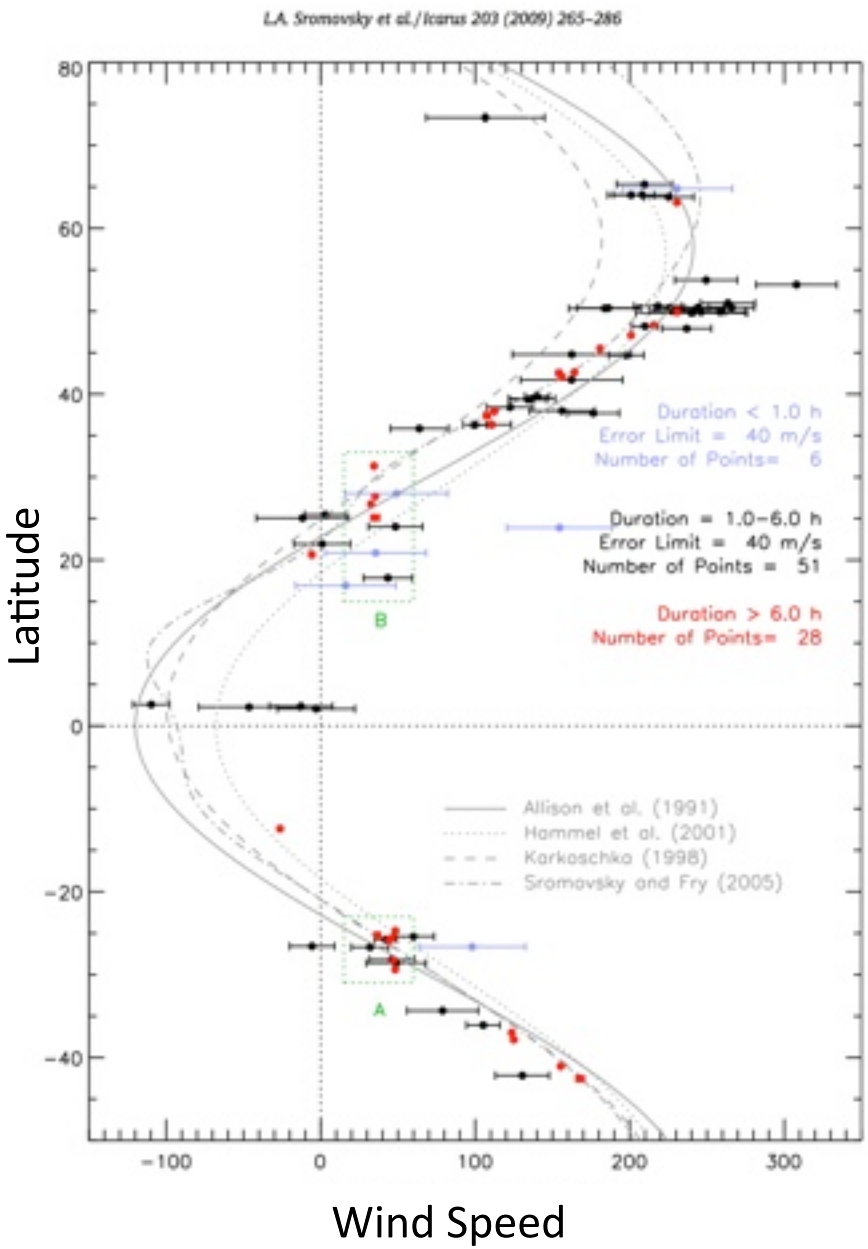
Desire

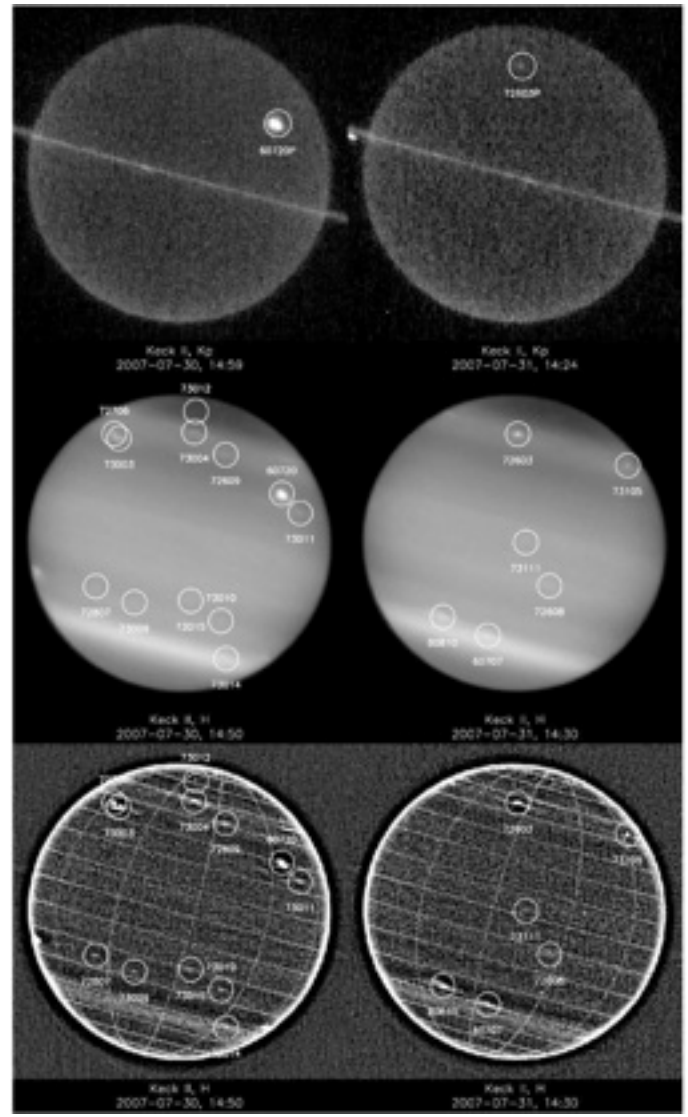
- Noble gas abundances
- Deep methane abundance from below cloud
- Other species: hydrocarbons, S, N...
  - Reveals formation mechanism, interior structure, dynamics, magnetic field generation, more...
- Thermal structure



Marley & McKay (1999); cooling times from Nettelman

Winds & dynamic atmosphere of Uranus





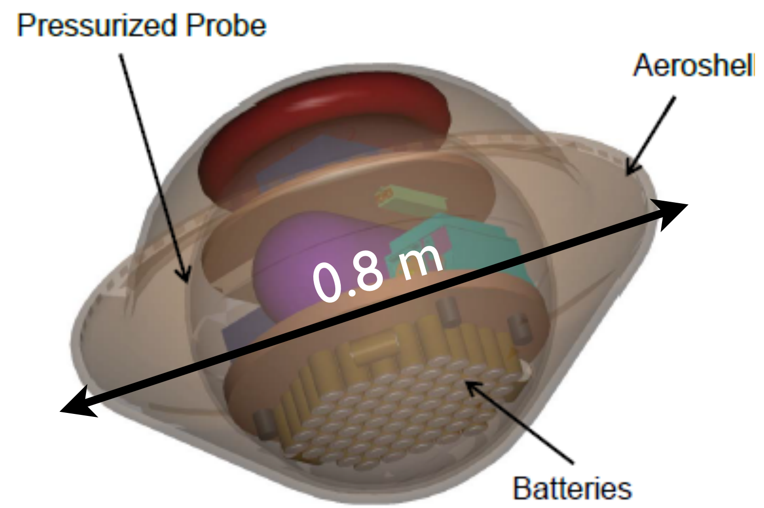
Decadal Survey Probe

Instrument	Method [Source for cost data]	Heritage Instrument (Mission Probe)
Mass Spectrometer	**Analogy to Mass Spec (Cassini probe)**	**MS (Galileo, Cassini)**
Atmospheric Structure Instruments	**Engineering estimate**	**(Galileo)**
Nephelometer	*NICM III System-Level Parametric Model-- Optical*	*Nephelometer (Pioneer Venus)*
Ultra-Stable Oscillator (USO)	*Analogy to USO [JHU/APL]*	*USO (New Horizons spacecraft)*

APL Study
for Decadal Review

Decadal Survey – Probe Design

Probe Type	**Pioneer Venus Small probe**
Entry Vehicle Diameter (m)	**0.76**
Cone Angle (deg)	**45**
Mass with margin (Kg)	**127 Kg (GLL 340 Kg)**
Instruments	**Mass spectrometer, temp-pressure sensors, USO and nephelometer**
Entry Flight Path Angle (deg)	**68**
Entry Velocity (km/s)	**22.35**
Launch date	**July-August 2020**
Arrival Time	**28-Jun-33**
Peak Deceleration (g Load)	**390**



Altitude for descent : 550 Km
Shallow descent up to 5 bar pressure.

No parachute on PV small probe

Table 3-16. Orbiter mass and power.

Orbiter Subsystem/Component	FLIGHT HARDWARE MASSES			FLIGHT HARDWARE POWER		
	Total CBE Mass (kg)	Contingency	Total MEV Mass (kg)	Total CBE Steady-State Power	Contingency	Total MEV Steady-State Power
Instruments	53.50 kg	16%	61.98 kg	41.5	30%	54.0
Structures & Mechanisms	185.00 kg	15%	212.75 kg	N/A	N/A	N/A
Propulsion (Dry Mass)	119.16 kg	6%	125.89 kg	155.7	14%	177.5
Command & Data Handling (C&DH)	14.65 kg	15%	16.78 kg	10.2	5%	10.7
Electrical Power (EPS)	88.50 kg	14%	101.13 kg	13.5	5%	14.2
Guidance, Navigation, and Control	46.10 kg	5%	48.40 kg	45.5	5%	47.8
Thermal Control (TCS)	35.00 kg	13%	39.65 kg	40.0	10%	44.0
RF Communications	59.99 kg	14%	68.33 kg	232.2	7%	247.9
Harness	32.00 kg	15%	36.80 kg	N/A	N/A	N/A
ORBITER DRY MASS/POWER	**633.89 kg**	**12%**	**711.71 kg**			
Dry Mass Margin	30% (Note 1)		272.57 kg			
ORBITER Maximum DRY MASS			**906.47 kg**			

Note 1: Margin is calculated based on Decadal Mission Study Ground Rules.

Dry Mass Margin% = (Maximum Dry Mass–CBE)/(Maximum Dry Mass)

Table 3-18. Entry probe mass and power.

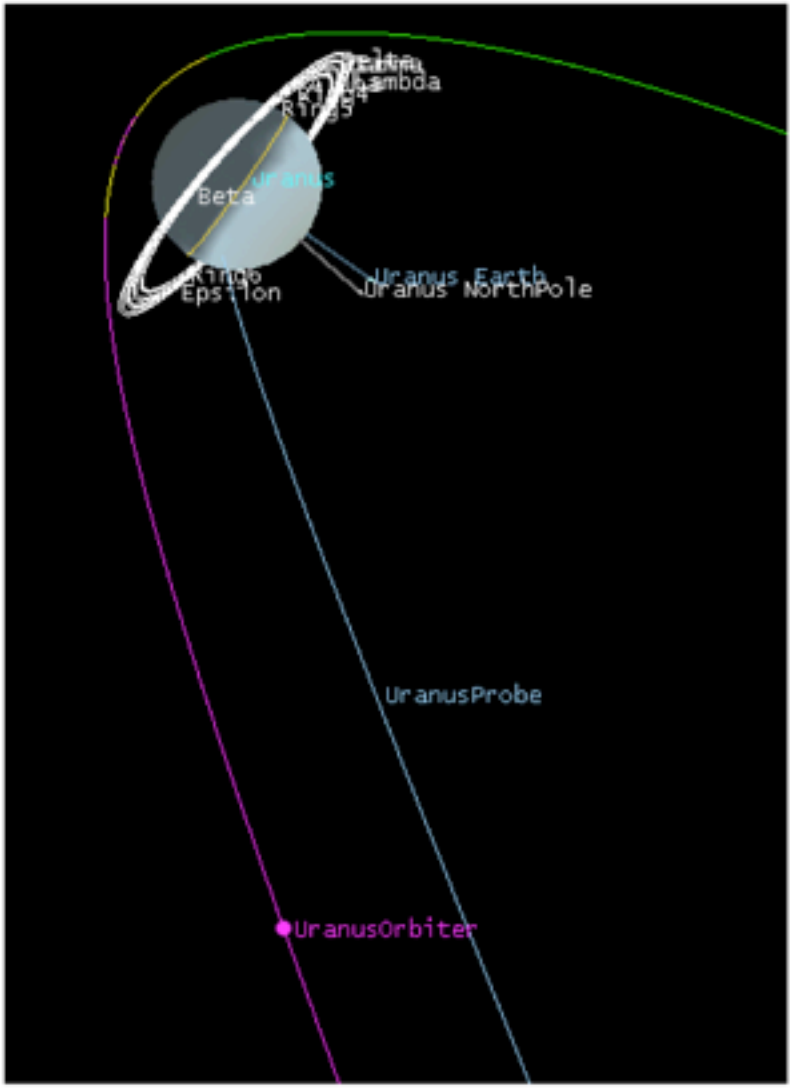
Probe Subsystem/Component	FLIGHT HARDWARE MASSES Total CBE Mass (kg)	Contingency	Total MEV Mass (kg)	FLIGHT HARDWARE POWER Total CBE Steady-State Power	Contingency	Total MEV Steady-State Power
Instruments	14.70 kg	17%	17.13 kg	21.7	30%	28.2
Structures & Mechanisms	49.50 kg	15%	56.93 kg	N/A	N/A	N/A
Command & Data Handling (C&DH)	4.00 kg	15%	4.60 kg	3.8	30%	4.9
Electrical Power (EPS)	8.70 kg	30%	11.31 kg	N/A	N/A	N/A
Thermal Control (TCS)	1.36 kg	15%	1.56 kg	7.0	10%	7.7
Communications	5.21 kg	9%	5.66 kg	21.1	19%	25.2
Harness	5.40 kg	15%	6.21 kg	N/A	N/A	N/A
PROBE DRY MASS/POWER	**88.87 kg**	**16%**	**103.40 kg**			
Dry Mass Margin	30% (Note 1)		38.21 kg			
PROBE Maximum DRY MASS			**127.08 kg**			

Note 1: Margin is calculated based on Decadal Mission Study Ground Rules.

Dry Mass Margin% = (Maximum Dry Mass–CBE)/(Maximum Dry Mass)

Orbiter and Probe Trajectories Post Orbiter Deflection Maneuver

- One day after Probe release (U-28 days), the Orbiter will perform an Orbiter deflection maneuver (~ 30 m/s) to target at the UOI B-plane aim point
- Orbiter is behind Probe with line-of-sight communication link
- Both Orbiter and Probe are visible from Earth
- Both Orbiter and Probe will not cross the rings



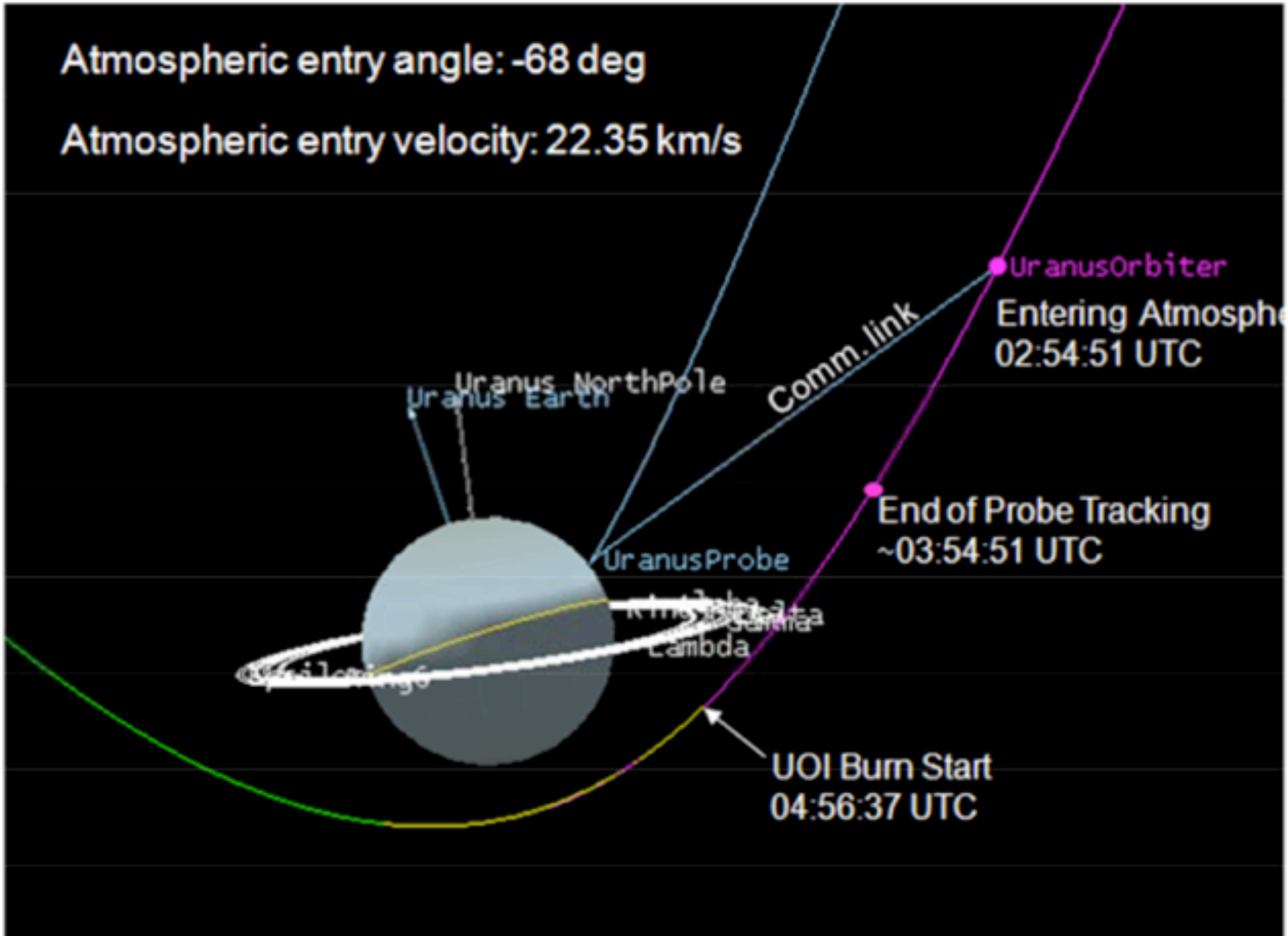


Figure 3-9. Probe entry and UOI geometry.

Probe Deceleration

Entry speed ~ 22 km/sec

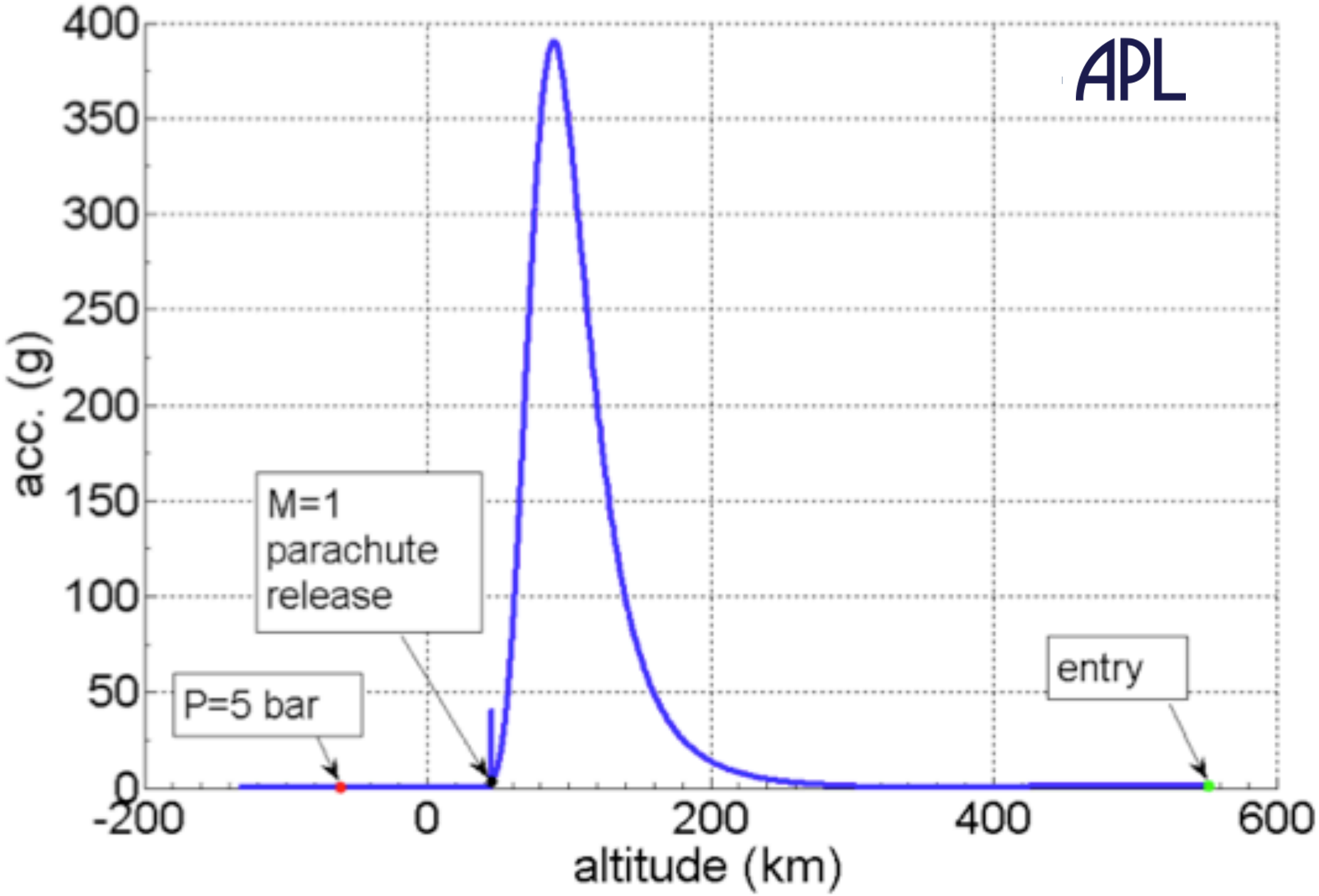


Table 3-22. Mission design: Probe entry.

Parameter	Value	Units
Probe release prior to Uranus arrival	29	days
Probe entry velocity	22.3	km/s
Entry angle	–68	deg
Peak deceleration loads	372	g
Peak heat rates	5511	W/cm^2
Peak heat loads	38.1	kJ/cm^2
Time to deploy parachute from entry interface	62	s
Measurement pressure range	0.1–5	bar

TPS Gap?

What are TPS Requirements?

- Peak deacceleration
- Pressure
- Heat load
- Phenolic Impregnated Carbon Ablator (PICA) or new TPS?

Uranus Probe Concept study

This study is funded by the Entry Vehicle Technology project under the In-Space Propulsion Technology program.

Objectives:

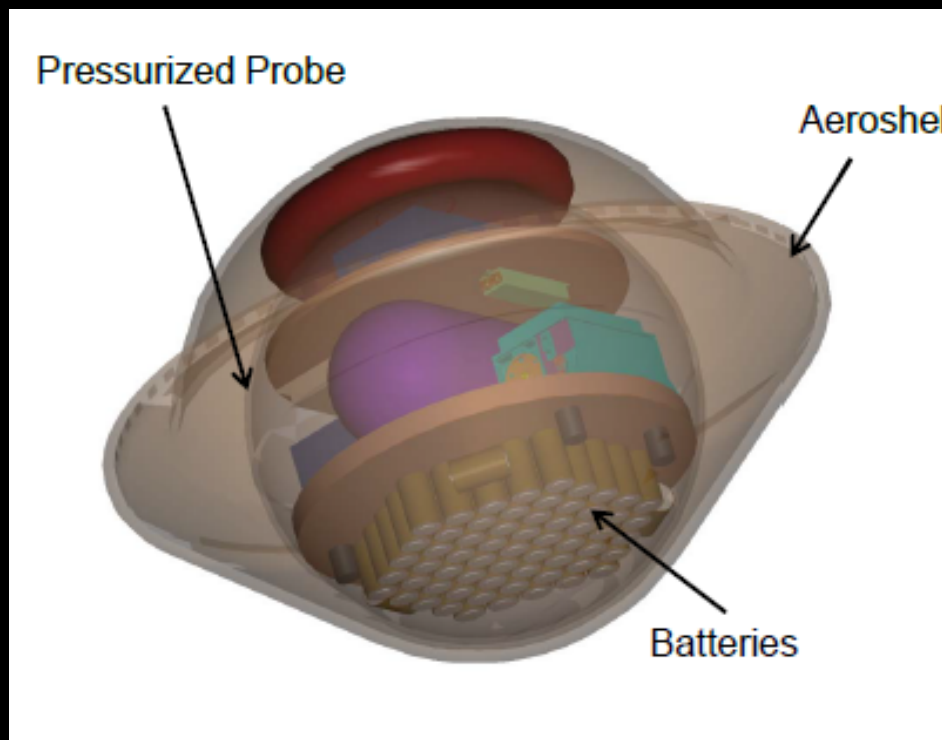
- **Establish probe entry environments based on the Flagship mission outlined in the Planetary Science Decadal Survey for 2013-2023.**
- **Define Uranus entry trade space by performing several parametric studies for various trajectory options, including ballistic and aerocapture entry**
- **Identify entry technologies that could be leveraged to enable a viable mission to Uranus and meet science objectives**

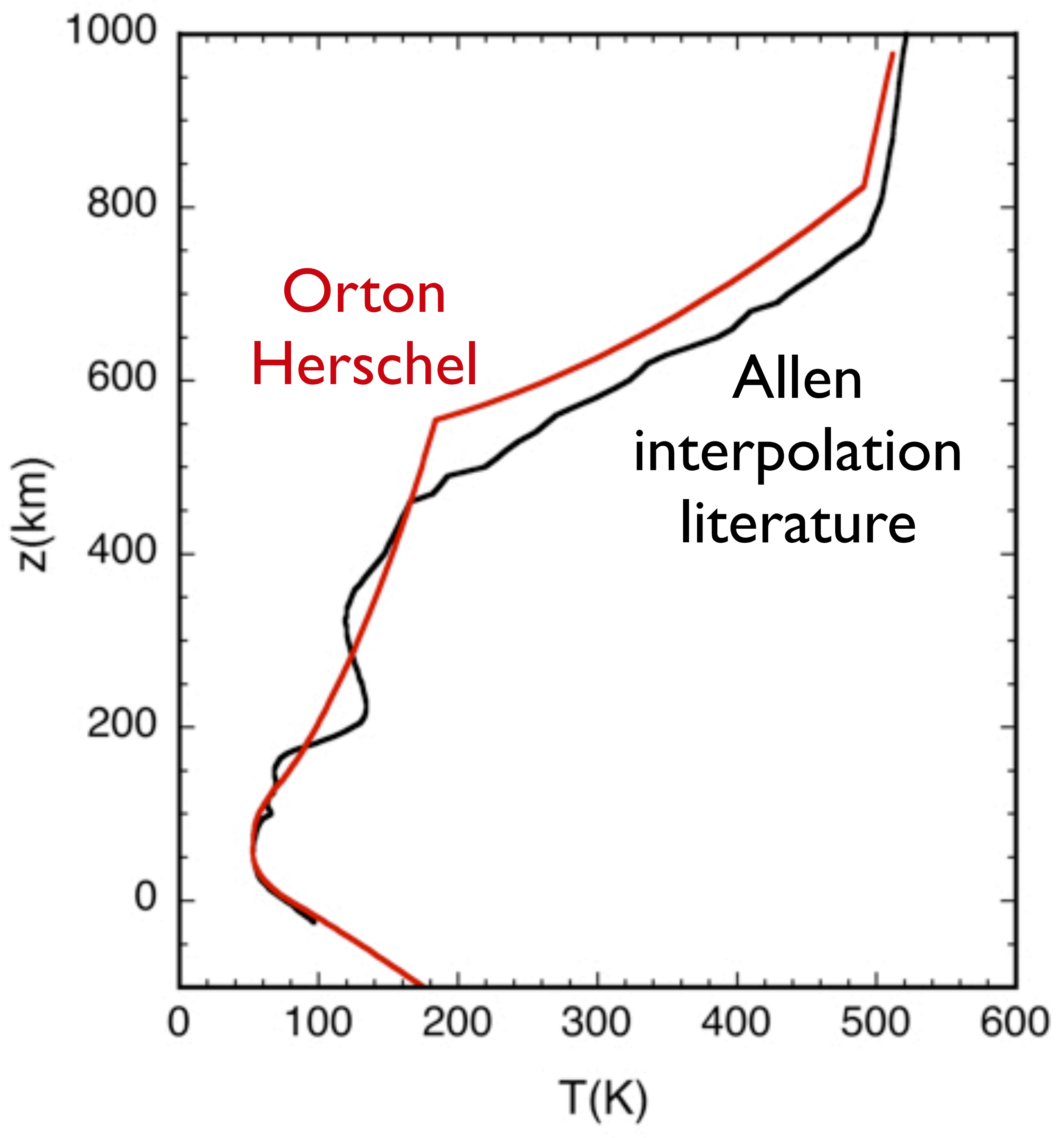
Current Status

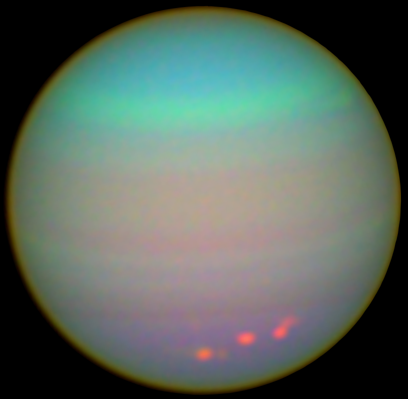
- **An engineering atmospheric model based on previous models and measurements has been developed to perform entry analysis. This model covers 0 to 5000 km altitude.**
- **Analyses have been performed for a range of entry flight path angles (EPFA) with ballistic coefficient varying from 150 kg/m^2 to 400 kg/m^2 for several entry vectors.**
- **Parametric studies of a range of probe masses and diameters are being conducted.**
- **Based on entry parameters (heat flux, pressure, heat load etc.), Thermal Protection System (TPS) material masses, as well as minimum performance criteria for new TPS materials, will be established.**
- **A comparative study between aerocapture and ballistic entry options is in progress.**

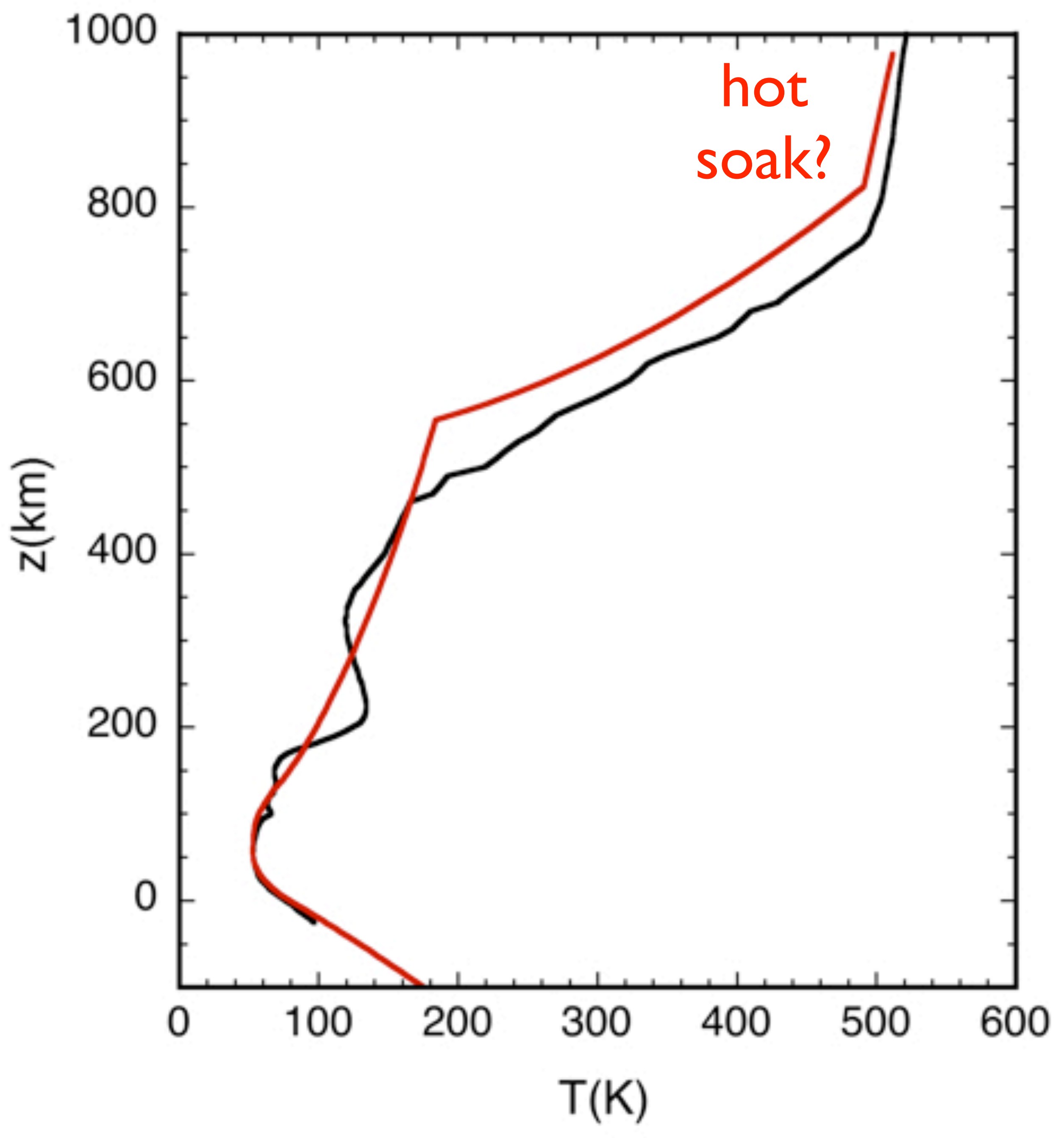
Note: The final results of this study will presented at 2014 IEEE and/or IPPW meetings.

Lessons Learned
So Far

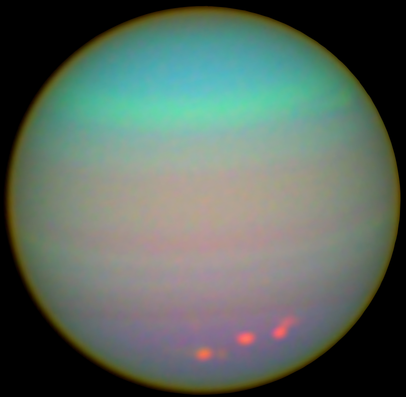


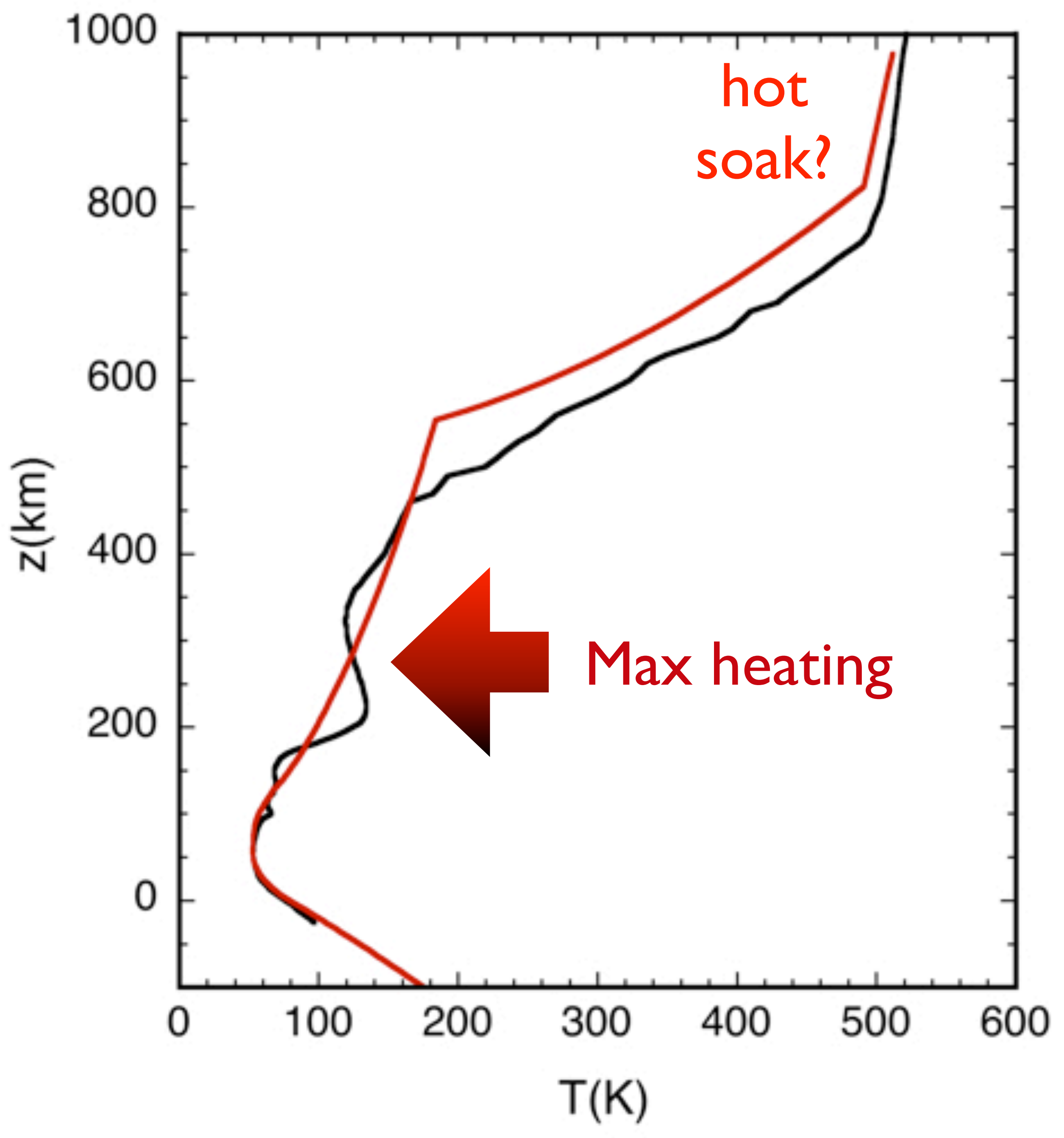

Orton
Herschel
Allen
interpolation
literature
z(km)
T(K)
0
200
400
600
800
1000
0
100
200
300
400
500
600

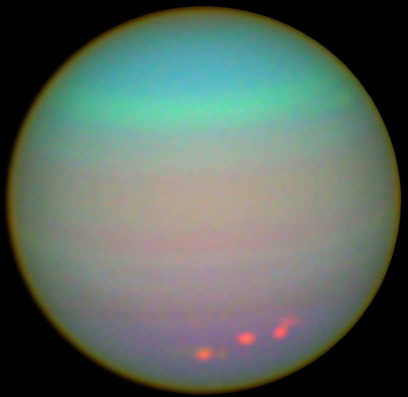


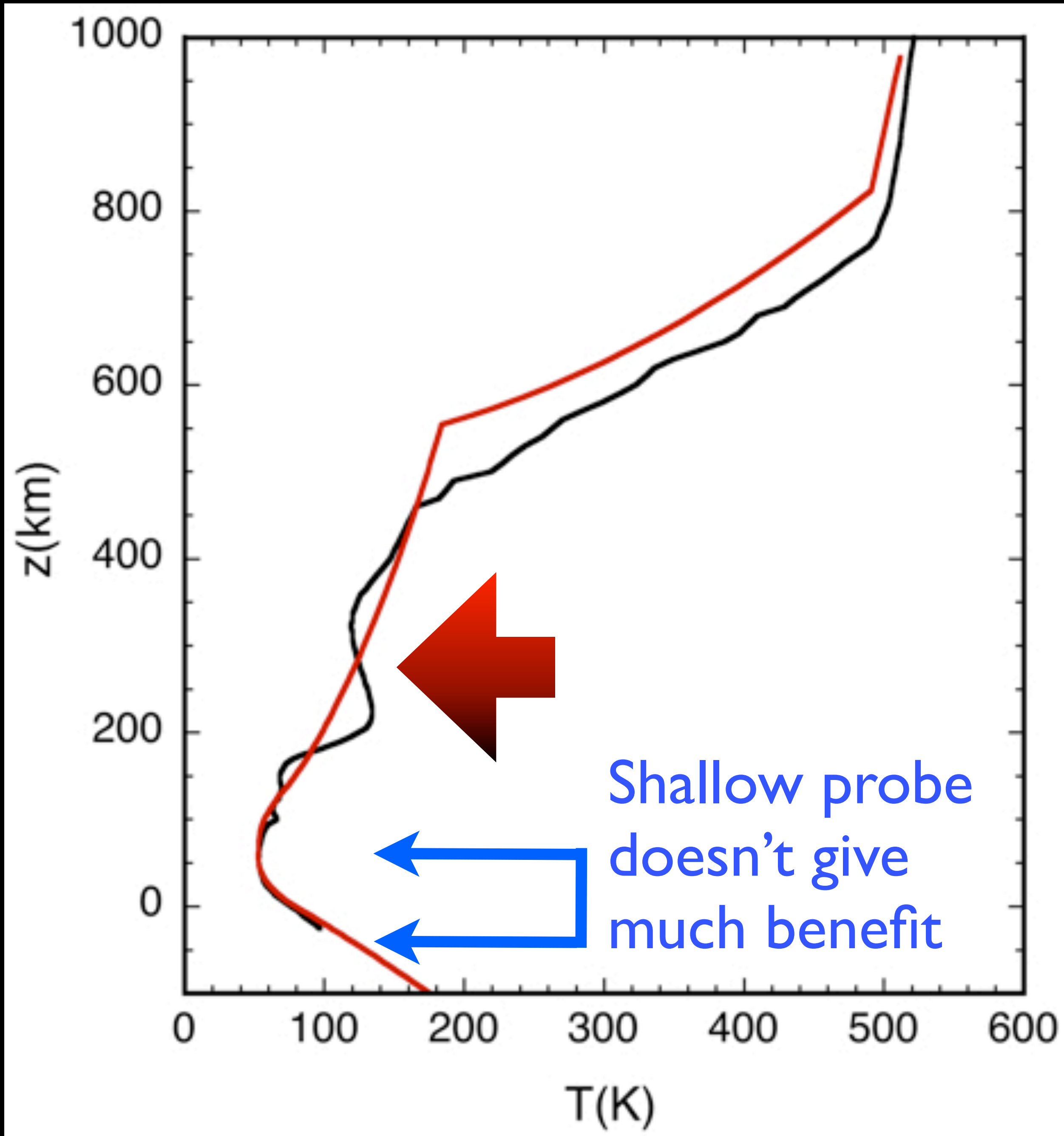


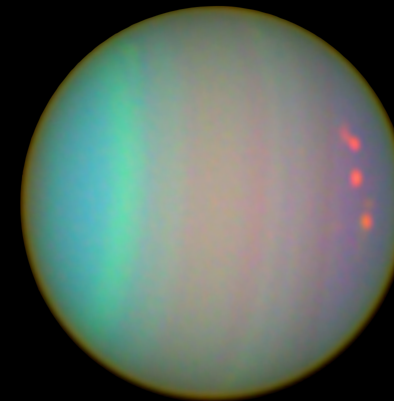
hot
soak?
z(km)
T(K)
0
100
200
300
400
500
600
0
200
400
600
800
1000

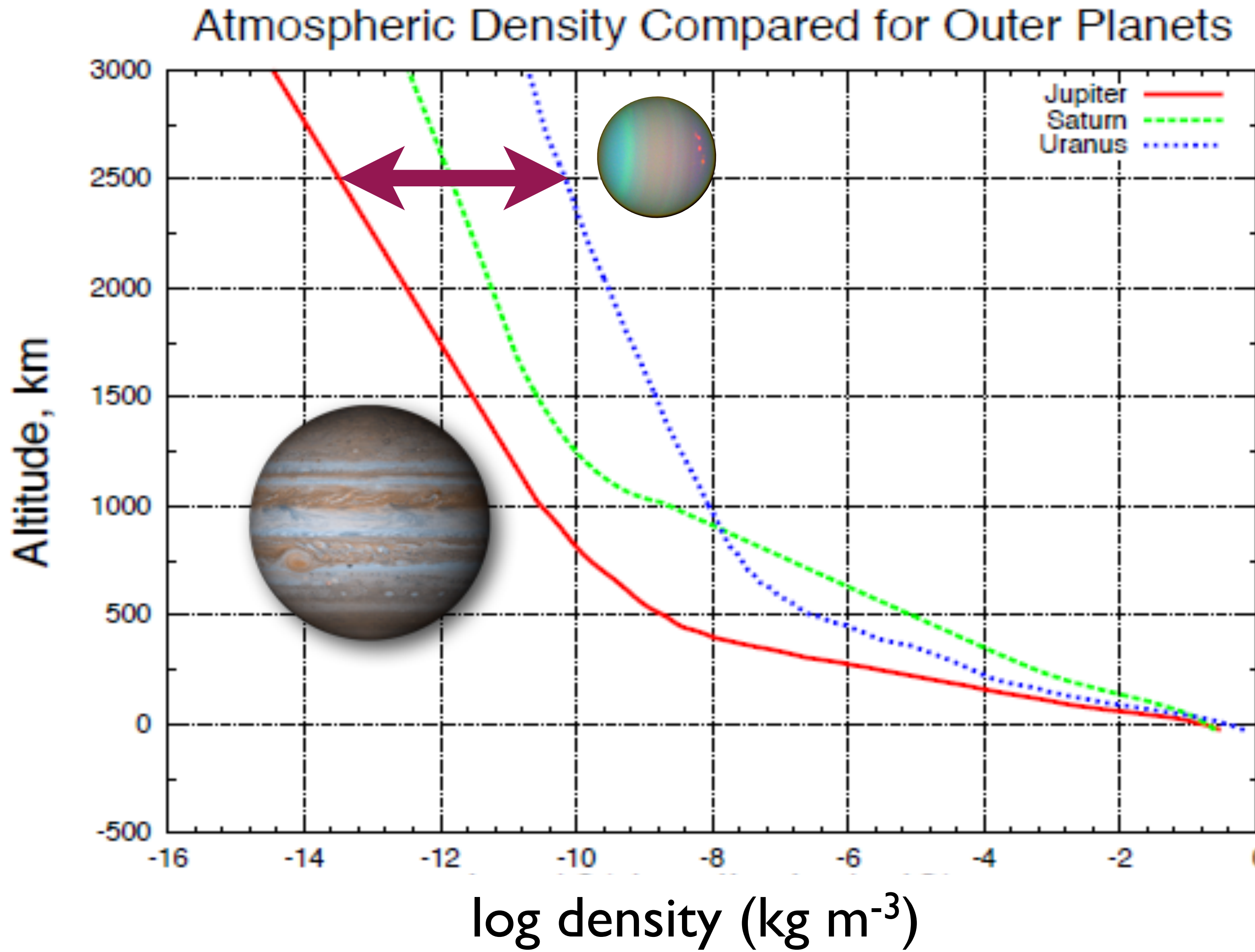



hot
soak?
Max heating
z(km)
T(K)
1000
800
600
400
200
0
0
100
200
300
400
500
600




z(km)
1000
800
600
400
200
0
0
100
200
300
400
500
600
T(K)
Shallow probe
doesn't give
much benefit



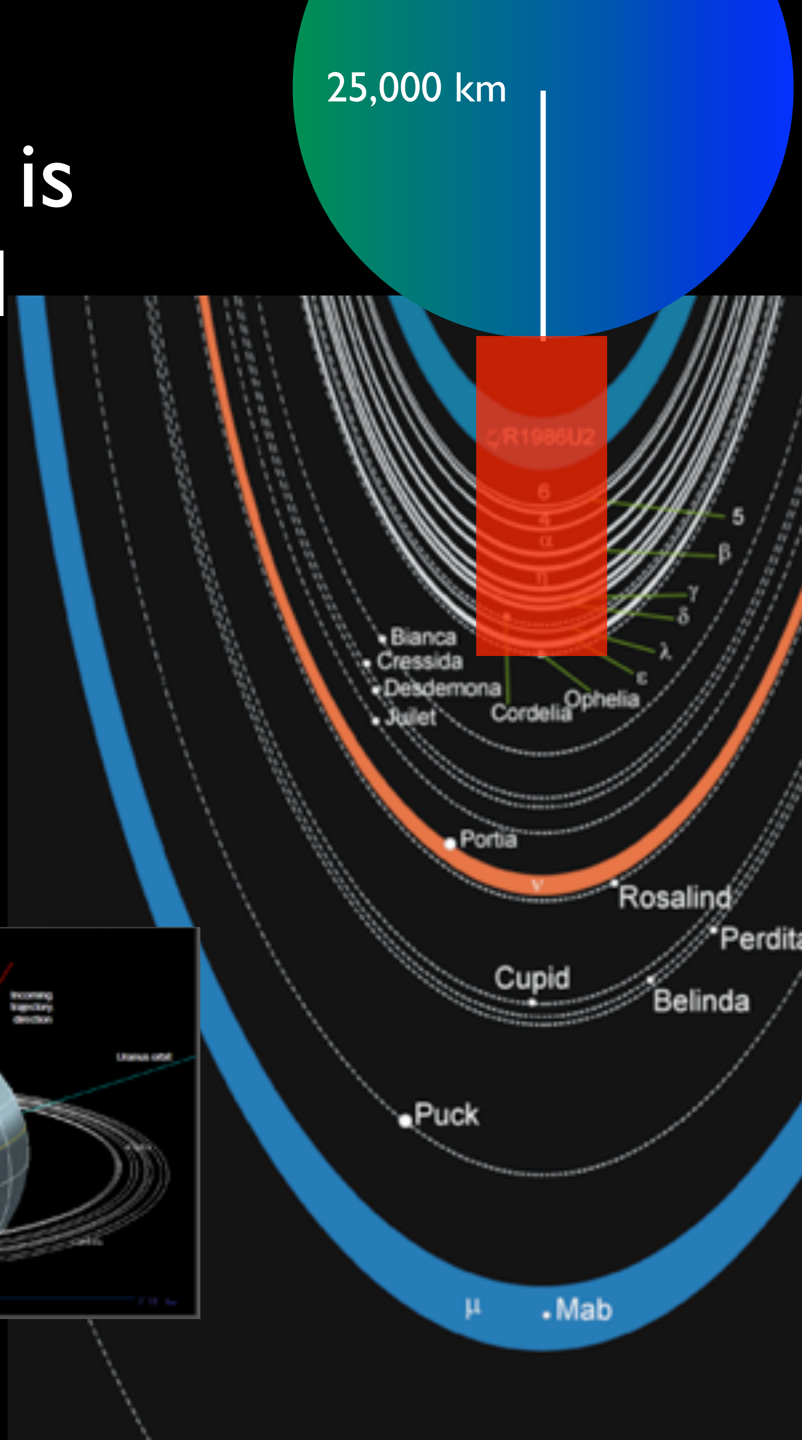

Atmospheric Density Compared for Outer Planets
Altitude, km
3000
2500
2000
1500
1000
500
0
-500
-16
-14
-12
-10
-8
-6
-4
-2
0
Jupiter
Saturn
Uranus
log density (kg m^-3)

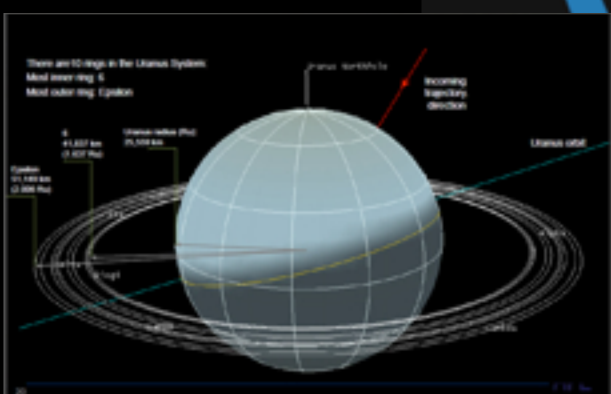
Ring avoidance is non-trivial

Phil Nicholson

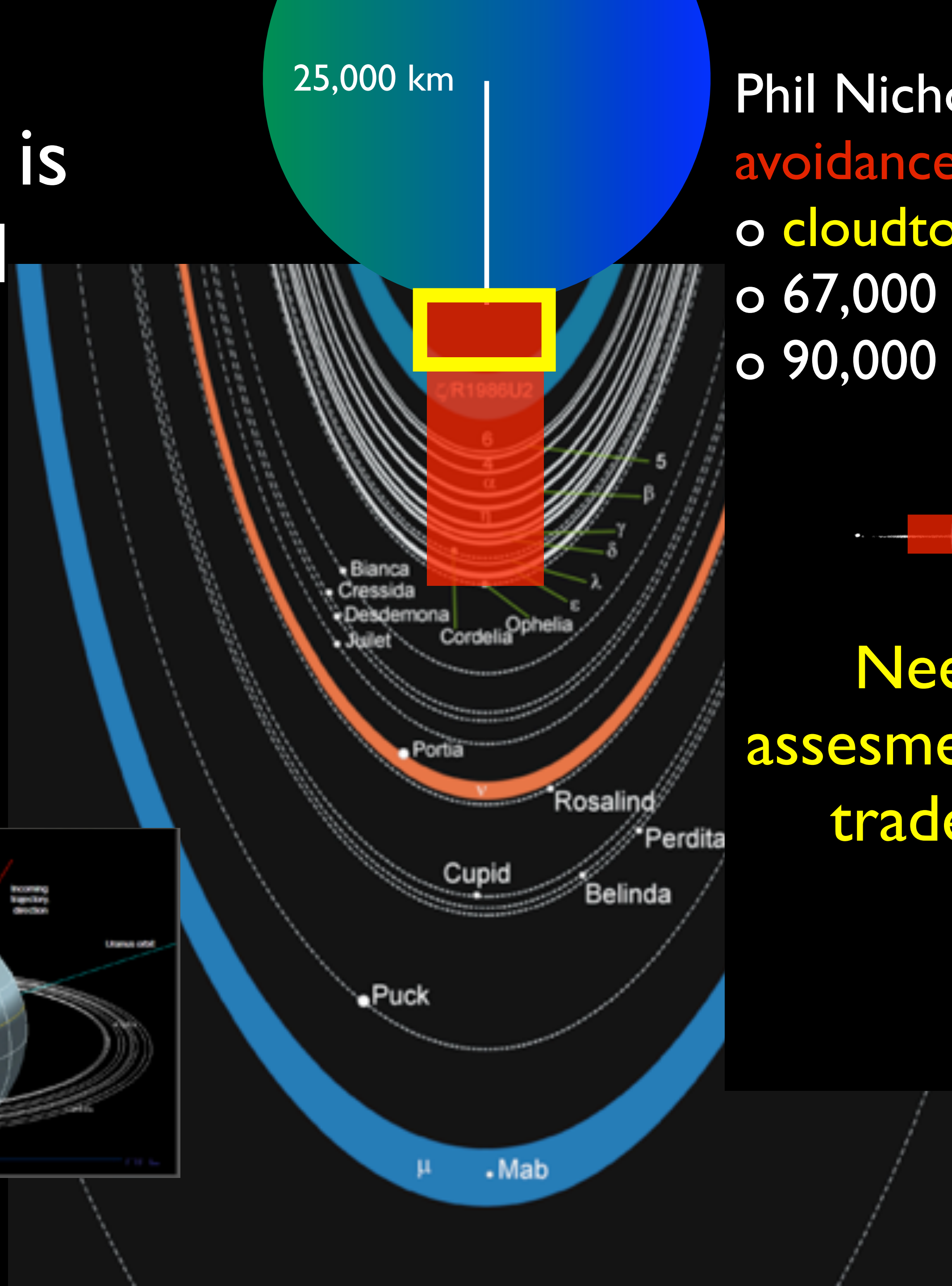
avoidance zone

- o cloudtops to 52,000 km
- o 67,000 +/- 2,000 km
- o 90,000 +/- 9,000 km





Ring avoidance is non-trivial

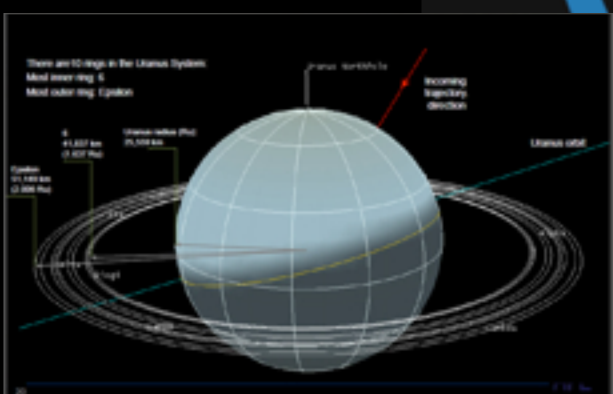


Phil Nicholson

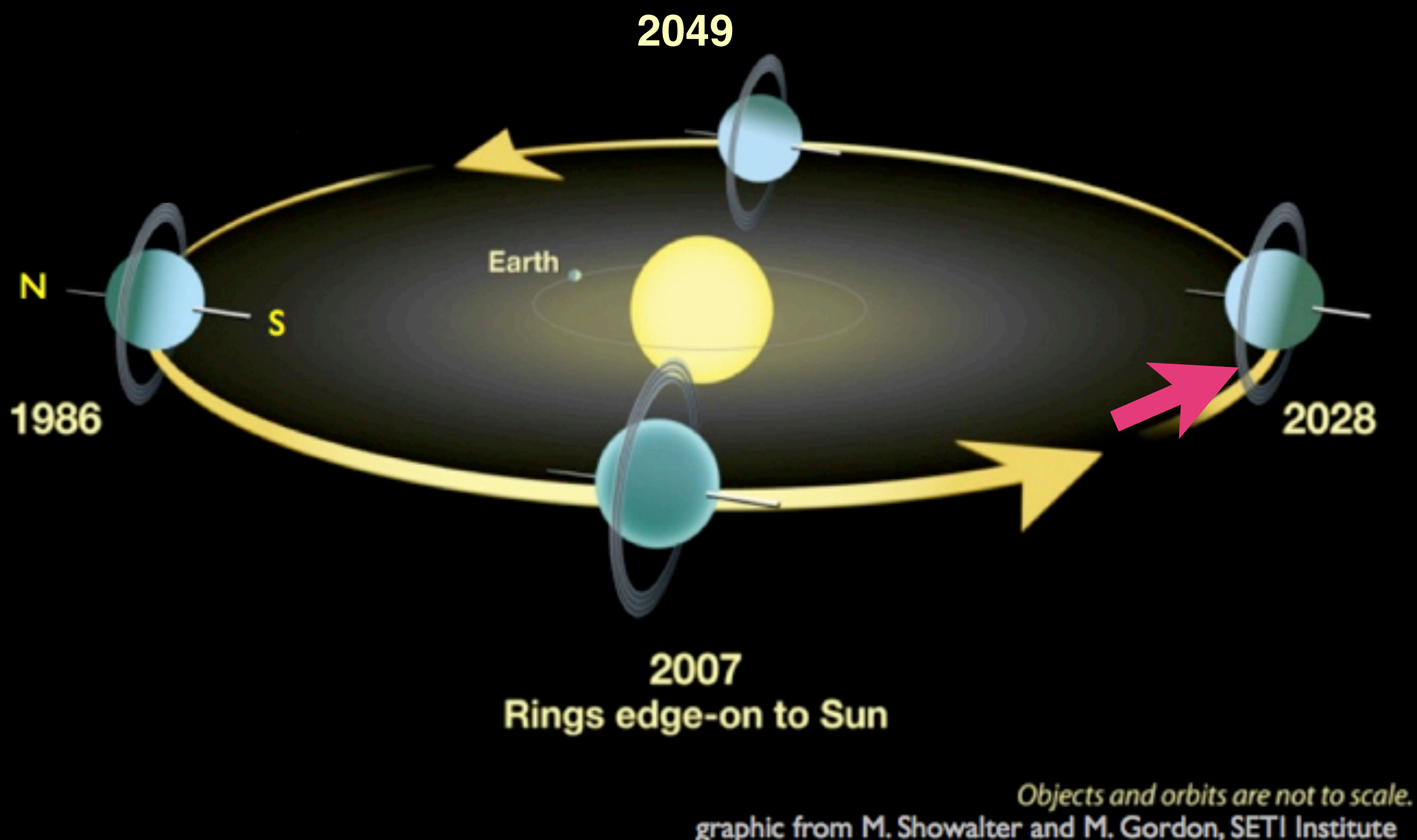
avoidance zone

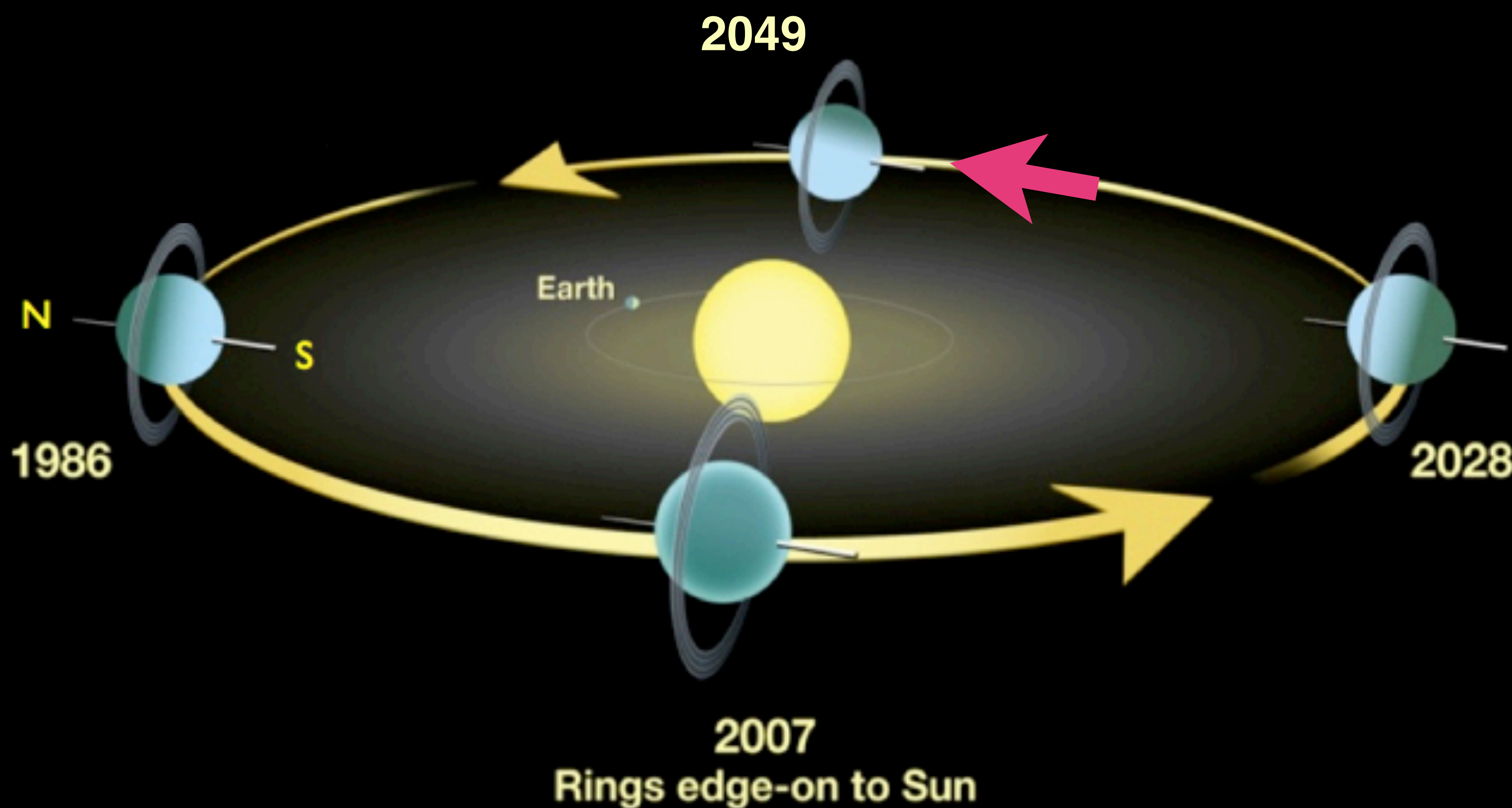
- cloudtops to 52,000 km
- 67,000 +/- 2,000 km
- 90,000 +/- 9,000 km

Need a fuller assesment of mission trades and risk



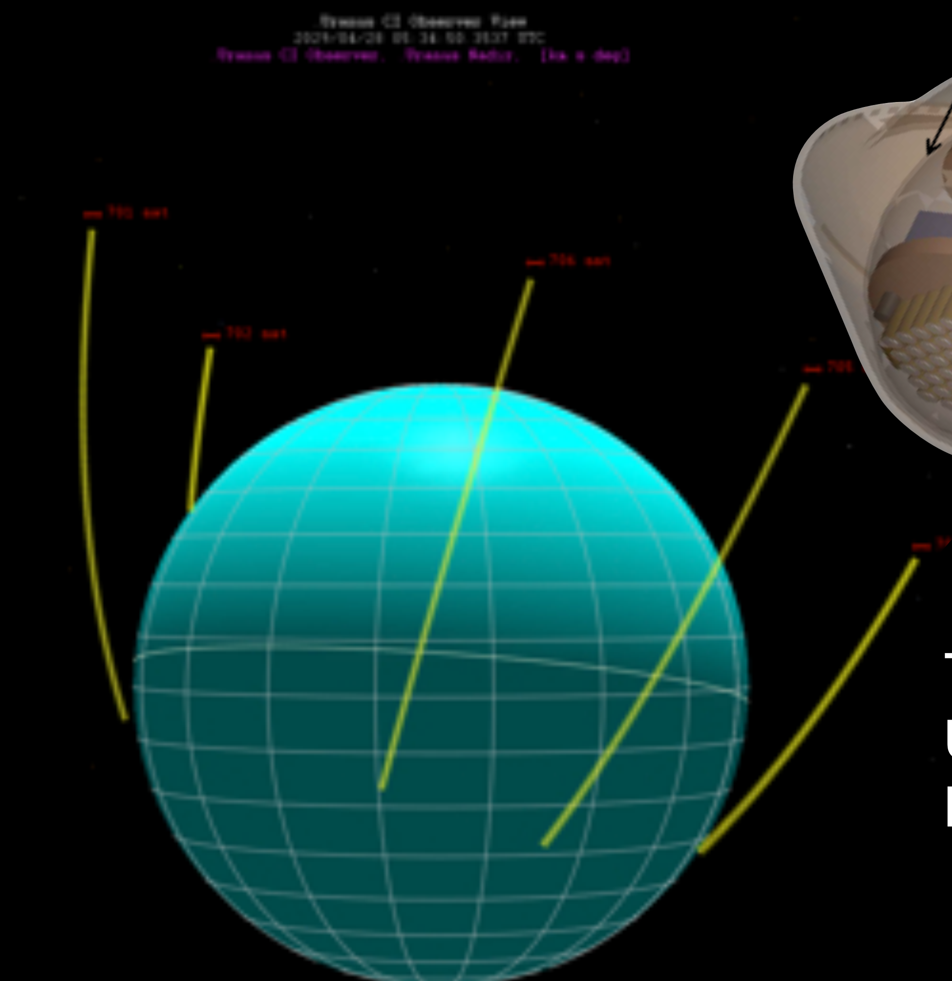
Rings as an Obstacle Depends on Arrival Date

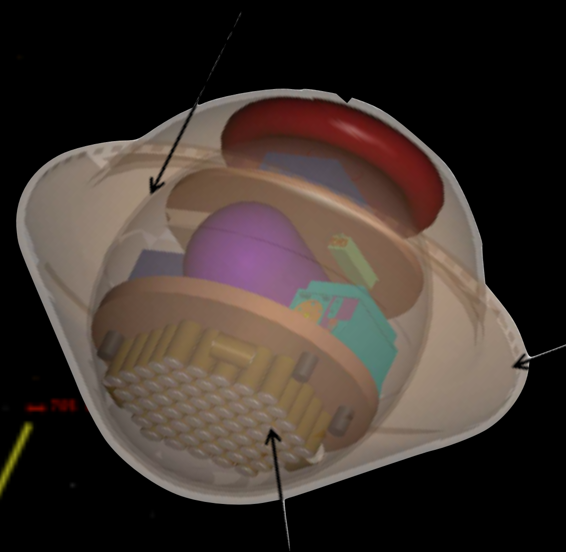




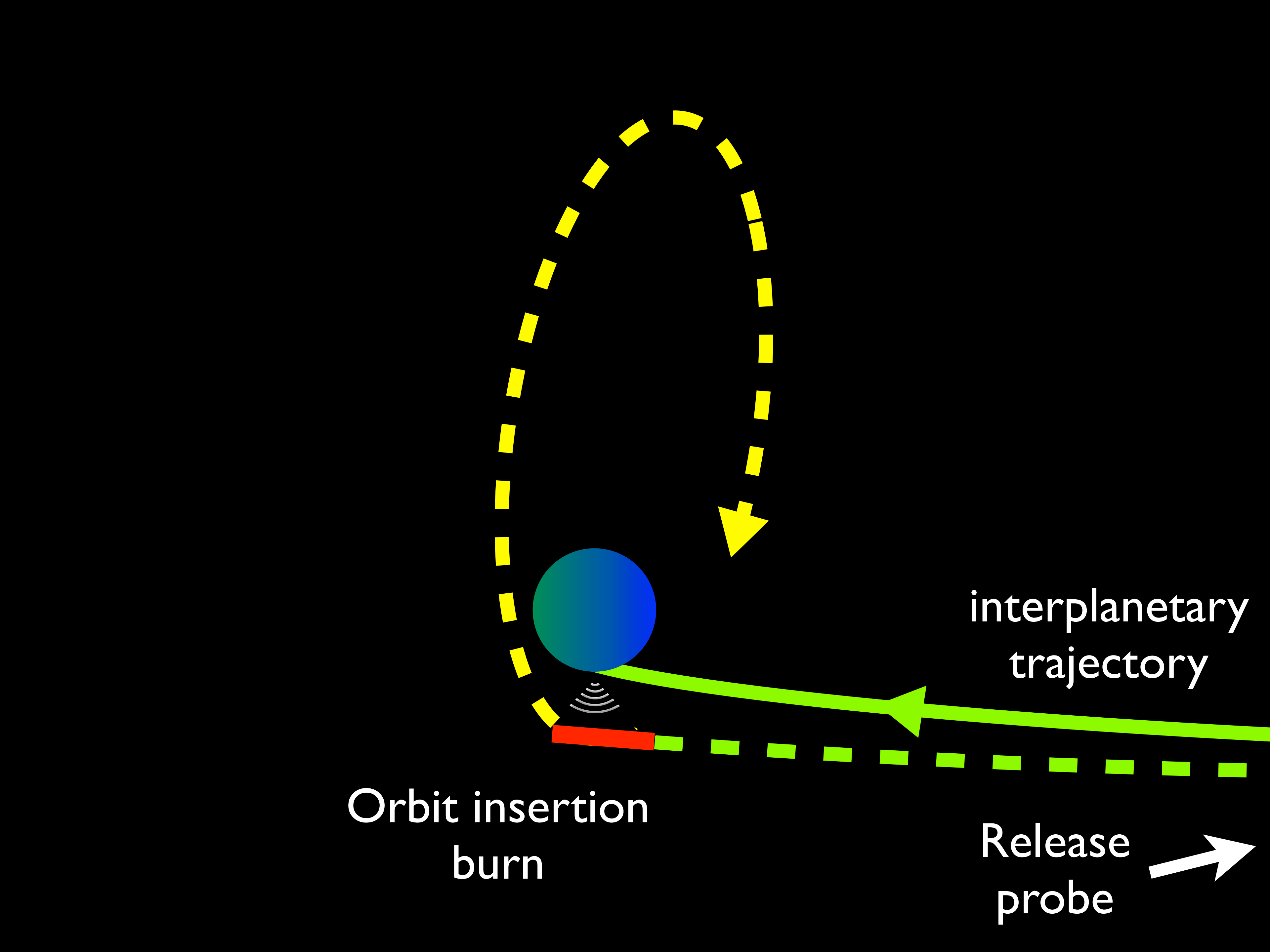
Objects and orbits are not to scale.
graphic from M. Showalter and M. Gordon, SETI Institute

Direct Entry Issues





Typical interplanetary trajectory to Uranus gives entry velocity of ~23 km/sec


interplanetary trajectory
Orbit insertion burn
Release probe

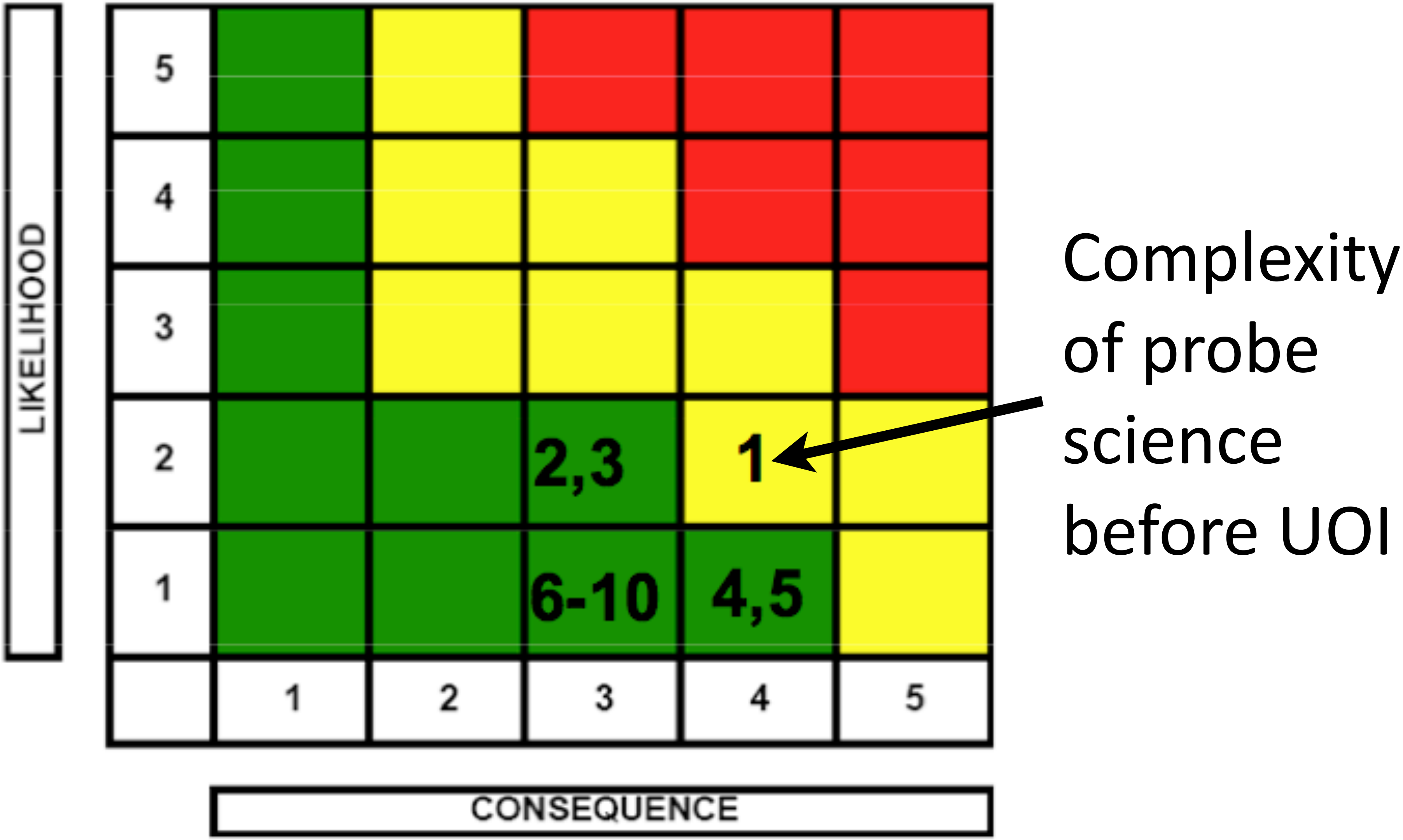
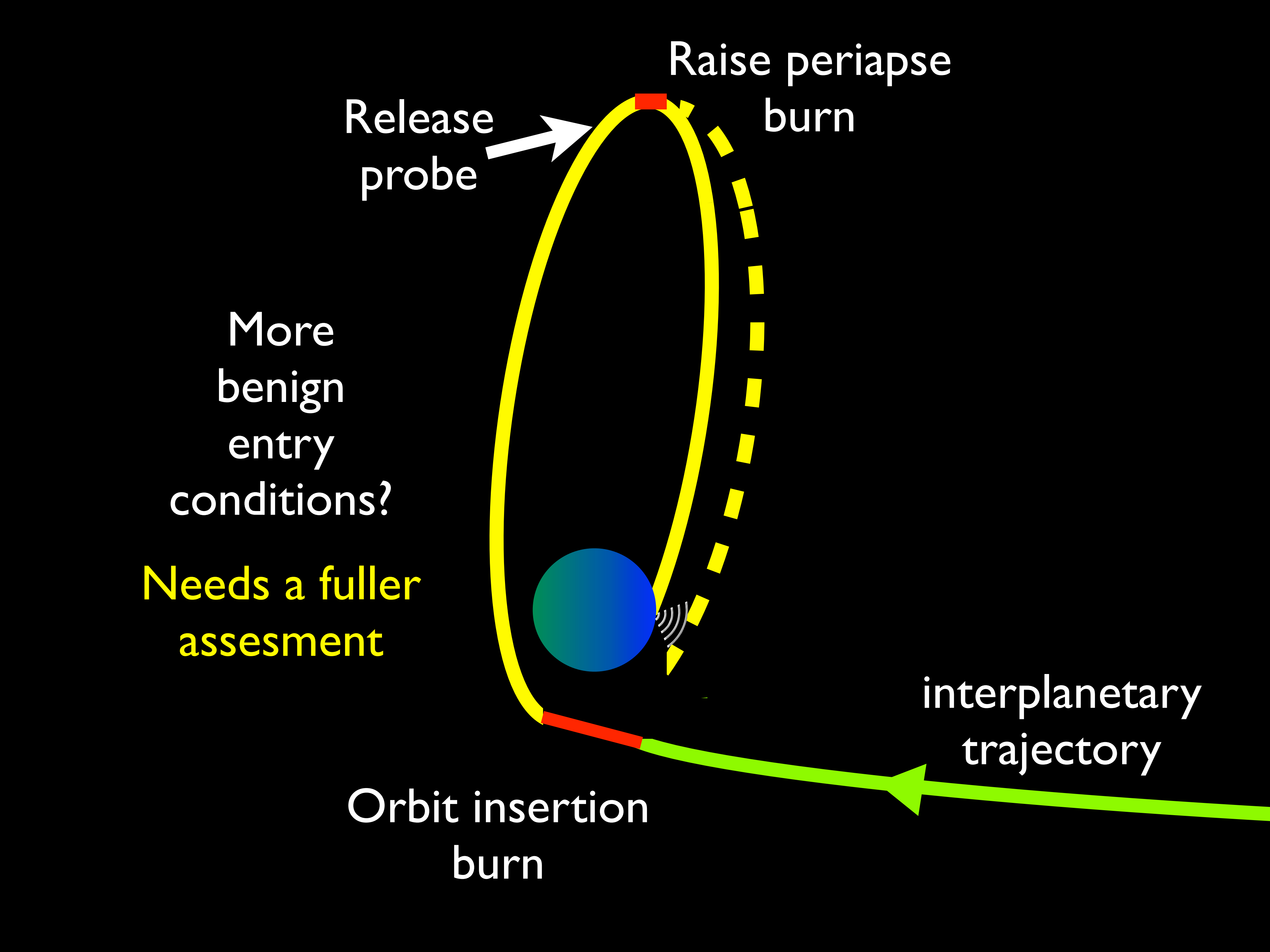


Figure 3-14. Risk matrix.

APL



Raise periapse burn
Release probe
More benign entry conditions?
Needs a fuller assesment
interplanetary trajectory
Orbit insertion burn

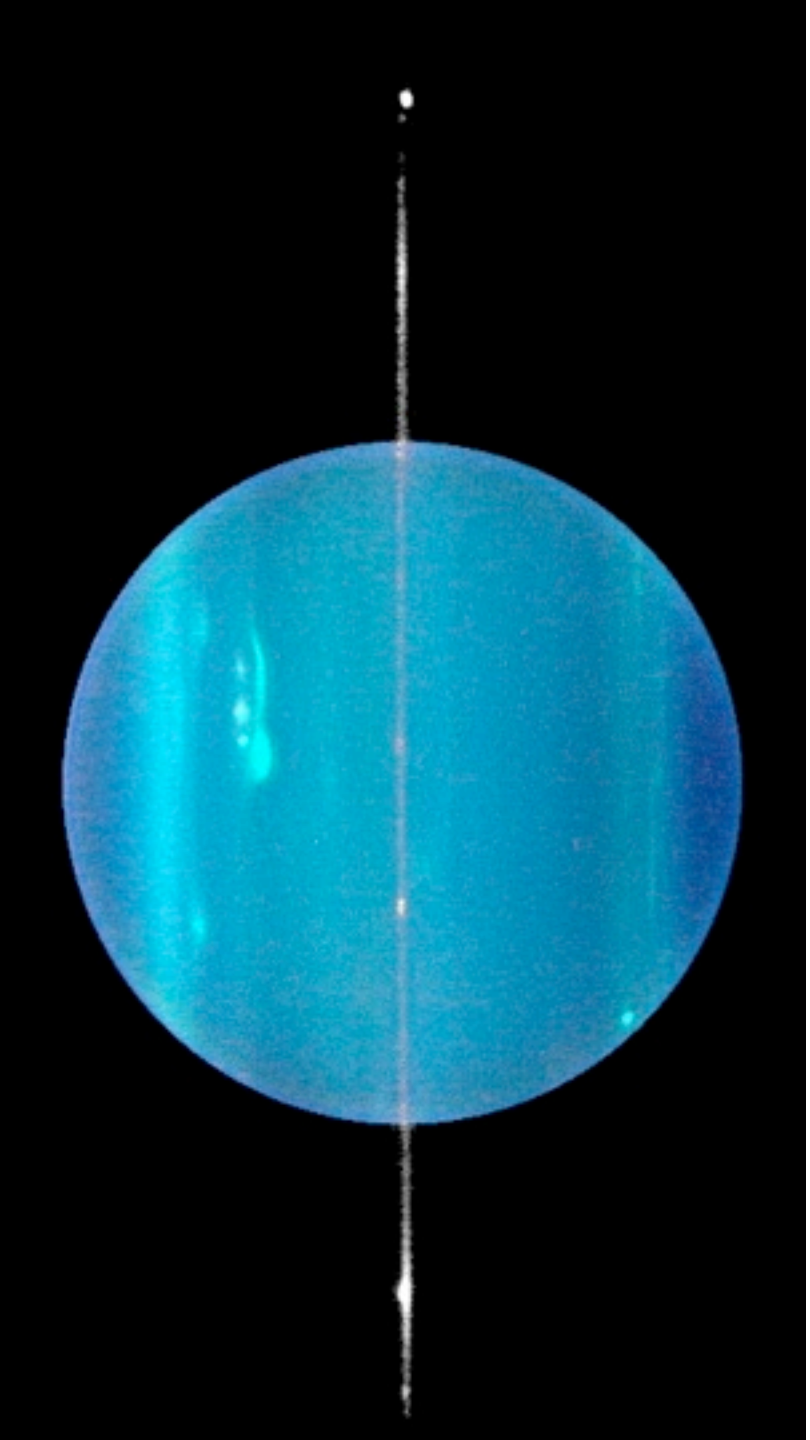


Image courtesy H. Hammel

Uranus Orbiter/Probe

- Broad scientific reach, with significant gains across many disciplines
  - atmospheric dynamics, chemistry, radiation balance, planetary interiors, magnetic fields, Sun-planet connections, satellite science, ring science
- Strong ties to exoplanet research
- Entry probe TPS study is ongoing
- Full mission design requires a richer study

Entry probe appears very doable and dramatically increases mission science yield. Details on TPS requirements next year.

Backup: 2030's Launch Dates

Earth Launch	Earth Launch C3	Jupiter Flyby	Jupiter Vinf	Jupiter Flyby Alt	Uranus Arrival	Uranus Vinf	Mass at Uranus Arrival	Time of Flight
5/4/2033	89.1136	3/4/2036	6.09 km/s	422907 km	4/6/2049	3.54 km/s	933.2 kg	15.93
4/30/2033	91.5849	1/23/2036	6.03 km/s	447728 km	4/6/2047	4.42 km/s	858.9 kg	13.94
4/27/2033	94.6729	12/13/2035	6.01 km/s	405352 km	4/6/2045	5.94 km/s	764.5 kg	11.95
4/24/2033	97.6144	11/14/2035	6.02 km/s	350880 km	4/6/2044	7.01 km/s	687.4 kg	10.96
4/22/2033	99.8001	10/23/2035	6.04 km/s	310076 km	9/17/2043	7.73 km/s	624.2 kg	10.41
6/12/2034	86.8624	3/27/2036	7.75 km/s	1285134 km	3/17/2043	8.69 km/s	1003.0 kg	8.77
7/20/2035	103.4289	1/3/2037	10.76 km/s	2780565 km	1/14/2044	7.88 km/s	528.2 kg	8.49
5/8/2033	84.8241	5/9/2035	6.80 km/s	116255 km	7/22/2041	11.52 km/s	1068.5 kg	8.21
7/20/2035	104.2441	12/31/2036	10.89 km/s	2672153 km	10/6/2043	8.30 km/s	508.1 kg	8.22
7/20/2035	105.2676	12/26/2036	11.03 km/s	2553608 km	6/28/2043	8.74 km/s	485.7 kg	7.95